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FEASIBILITY OF MULTISENSOR COMBINED DISPLAYS

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In this study of multisensor displays, the objectives were to consider different display formats, and to suggest simple, efficient ways of implementing electronic and optical methods of combining images. The study is part of a more general U.S. Navy program to develop a system for combining the information from several sensors on a single display surface.

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Until recently, the complexity and number of cockpit instruments increased with the complexity of aircraft and the functions for which they could be used. Then, because of advances in display technology, multifunctional, integrated display systems were developed. Their immediate appeal is that they require relatively little cockpit panel space. However, there are other, perhaps more positive, potential uses of multifunctional displays. It is by exploring these potentialities that we are likely to be led to new cockpit instrument panel guidelines.

Our main concerns in presenting images from a number of sources are for clarity of information and speed of assimilation. A consideration of image content shows that there can be a wide range of relationships between two or more images that are to be presented together. The relationship is determined by the pointing angle of the sensors delivering the imagery, by the geometry of the images, and by the fields of view/magnifications being used.

Imagery from several sources can be used in several ways. First, an observer may need to compare the outputs of two or more sources to derive a kind of information composite. Second, an enhanced, composite image might be produced by combining separate images on the observer's screen. Third, the observer may need to monitor information from more than one source. Fourth, transitions from one image source to another may be facilitated by some form of multiple-image presentation.

Eight methods of presenting multiple images were identified. They included superimposition, juxtaposition in time, split screen, and various forms of insetting. The appropriateness of these eight methods for each of the four uses of multiple-image presentation was considered. Of the 32 combinations of uses and methods, 11 were judged to be promising, a further 11 were possible, while the remaining 10 were inappropriate.

Various sensors and displays, as well as techniques for image combining, scan conversion and symbol writing were reviewed. They were evaluated in terms of their applicability to the multi-image presentation cases listed above. Of eight image-combining techniques evaluated, the one with the greatest potential for a low-cost, near-term, multi-function display was judged to be optical image combining. Digital computer techniques for more complex applications were also discussed.

FOREWORD

The study reported in this document was conducted by the Systems and
Research Center of Honeywell Inc. from May through December 1976 under
sponsorship of the Office of Naval Research, 800 North Quincy Street,
Arlington, Virginia 22217. The work was identified by Systems and Research
Center number F0455. Robert J. Hughes and Leon G. Williams, PhD,
served as co-principal investigators under the program management of
A. F. Kanarick, PhD. Significant technical contributions were made by
John Bloomfield, PhD in multi-image presentation and by Patrick D. Pratt
in implementation. The work has been completed and this report released
for publication by the authors in December 1976.

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SECTION I
SUMMARY

In this study of multisensor displays, the objectives were to consider different display formats, and to suggest simple, efficient ways of implementing electronic and optical methods of combining images. The study is part of a more general U.S. Navy program to develop a system for combining the information from several sensors on a single display surface.

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Eight methods of presenting multiple images were identified. They included superimposition, juxtaposition in time, split screen, and various forms of insetting. The appropriateness of these eight methods for each of the four uses of multiple-image presentation was considered. Of the 32 combinations of uses and methods, 11 were judged to be promising, a further 11 were possible, while the remaining 10 were inappropriate.

In considering implementation we considered a number of image sources and several cases of multiple-image presentations. They are listed in Table 1-1 along with other important factors.

Various sensors and displays, as well as techniques for image combining, scan conversion and symbol writing were reviewed. They were evaluated in terms of their applicability to the multi-image presentation cases listed above. Of eight image-combining techniques evaluated, the one with the greatest potential for a low-cost, near-term, multi-function display was judged to be optical image combining. Digital computer techniques for more complex applications were also discussed.

Further research and development work is recommended. However, in both cases, it should be directed towards more specific applications. The following tasks are necessary:

For research

- Prioritization of four uses of multi-image presentation

- Prepare and conduct experiments and analyze data to determine the most appropriate method(s) of presenting multiple images for highest priority use.

Table 1-1. Requirements for Candidate Image-
Combining Concepts

Sensors

- PPI radar with slow frame rate
- FLIR and LLLTV with high quality imagery

Annotation

- Moving map
- Symbols and graphics

Image Combination Laser

- Radar and moving map
- Inset radar imagery into E-O imagery
- FLIR imagery inset into LLTV imagery
- Radar, FLIR, and LLLTV imagery sequentially or simultaneously
- Annotation for either radar or E-O imagery

Cockpit Environment

- High ambient illumination
- Limited head motion requirement
- Severe vibration

Display

- Minimum instrument panel space
- High visibility
- Head-down application assumed

Design

- Simple
- Reliable
- Low cost

For development

- Definition of mission to establish specific system requirements
- Definition of system components for image combining by means of performance tradeoffs
- Fabrication and evaluation of demonstration system

We are dealing with complex tasks and techniques. It will not be easy to discover the optimal ways of combining images. However, research such as that suggested should help in defining new cockpit design guidelines.

SECTION II
INTRODUCTION

OBJECTIVES

This study, part of a more general program, is to develop a system for combining the information from several sensors on a single display surface. The objectives of the current study were to consider different display formats, and to suggest simple, efficient ways of implementing electronic and optical methods of combining images.

ORGANIZATION

There are five main sections to this report. The first is an Introduction. The second, Multi Image Presentation, discusses ways of combining images, and describes those likely to be most useful. The third section, Implementation, details available equipment. It also contains a general description of ways various image combinations might be achieved, and this is followed by some illustrative examples. The fourth section is an Evaluation. The final section, Recommendations, presents conclusions and recommendations for further research and development.

This introductory section deals with the reasons for considering multifunctional, multisensor displays, describes the cockpit environment in which they may be used, and, finally, discusses the potential advantages that might be obtained by using these displays.

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WHY USE MULTISENSOR DISPLAYS?

From the early 1900s until recent times, there was an obvious trend in the way information was displayed in cockpits. Gradually, aircraft became more complex, and could be used in an increasing number of circumstances. There was a corresponding increase in the number, and in the complexity, of displays and dials. This trend could have continued until pilots were faced with an unmanageable multitude of display surfaces.

Fortunately, there are alternative methods of handling information. By using storage and processing devices, the trend has been arrested. Multi-functional, integrated cockpit display systems have been developed. Examples are provided by the U.S. Navy's Advanced Integrated Modular Instrumentation System (AIMIS) and Vertical Take Off and Landing System (VTOL), by the U.S. Air Force Digital Avionics Information System (DAIS) and the B-52 Electro-optical Viewing System (EVS).

At present, there is a transitional stage. This seems certain to be followed by a period in which there is an increasing emphasis on integrated, multi-functional displays.

The cockpit designer's problem was how to squeeze another dial, or display, into the already cluttered array facing the operator. Now, the designer has tools, developed through computer science and advances in display technology, that allows him/her to cut through the design constraints of conventional cockpit displays. However, it may be that he/she is wielding a double-edged sword. These constraints provide some of the basic guidelines of cockpit design. In eliminating them, the designer will find that he/she has excised many of the guidelines as well.

The immediate appeal of multifunctional, multisensor displays is that they are economical. One screen is less expensive than two, or three, and, more importantly, it takes less space. However, the use of these displays opens up many other possibilities.

Multisensor displays may improve both the quality, and flow of information. By combining different sensor outputs, it may be possible to enhance those features of the resultant, composite image that are relevant to the operator's tasks. In addition, with a multisensor display, the operator may be able to make smoother transitions between one sensor output and another.

These potential improvements in information could, in turn, lead to improvements in a number of the operator's tasks: navigation, piloting, target acquisition, tracking and battle damage assessment. These tasks might well be carried out more rapidly, with more accuracy, and/or with less effort by the operator.

There are several ways of combining images: multiple screens, juxtaposition in time, overlay, split screen and various forms of insetting. Investigations will have to be conducted to discover which techniques produce the optimal performance in various operating tasks. It is through such investigations that new cockpit design guidelines will appear.

We can expect the range of aircraft functions and activities to continue to increase in the future. Spatial and financial economy are important. But, another consideration will outweigh them soon, if is has not already. We must discover how to present information to pilots and navigators in the most easily, and rapidly assimilable way possible.

As a first step, this study concentrates on ways in which continuous real-time imagery might best be presented.

THE COCKPIT ENVIRONMENT

The cockpit environment is far from ideal.

Space is limited. One of the prime reasons for the confusion of instruments that confront the operator is that they have to be crammed into a very restricted area. As discussed in the previous section, multisensor displays may be of considerable importance in reducing this visual clutter.

There are other impediments in the visual environment. The operator's view of the world outside the cockpit is determined by the design of the aircraft; by the size of the windows, and the extent to which the body of the vehicle obscures the ground. In addition, many aircraft are equipped with some kind of Head Up Display (HUD). HUDs are used to present information directly on the windshield. A more sophisticated variant of this is the Helmet Mounted Display (HMD). In this case, a display is mounted on the visor of the operator's helmet. Both HUDs and HMDs are useful visual aids. However, when the observer is looking through them to observe cockpit instruments, they may be a hindrance.

The space limitations also affect the operator more directly. He/she has virtually no freedom of movement. On the other hand, he/she is subject to many forces caused by various movements, both large (forward motion, roll, pitch and yaw) and small (vibrations).

We must be aware of these factors, when developing multisensor displays. Anything that is added to the cockpit environment, must be compact, and robust, and should reduce visual clutter.

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POTENTIAL ADVANTAGES OF MULTISENSOR DISPLAYS

Multisensor displays could affect performance of a number of the operator's tasks: reconnaissance, navigation, piloting, target acquisition, tracking, fire control and battle damage assessment.

To perform these tasks, it may be necessary for the operator to use information from a number of sources, simultaneously, and/or sequentially. For example, consider a mission in which the operator has the task of assessing battle damage on a particular installation. He/she may need to look at map information and radar imagery. He/she will then be able to identify a particular area. Next, it may be necessary to switch to a low light level television (LLLTV) to see the area in detail. Finally, it may be advisable to make the damage assessment using a thermal image sensor, as well as the television.

Clearly, this task can be performed if the operator has a map and the necessary sensor-display systems. However, it may be easier to carry out the task using a multisensor display. First, the operator would look at projected map imagery and at the output of the radar. With their scales adjusted appropriately, simultaneous presentation on a single screen would allow a direct comparison. Having identified the ground area of interest, the operator could introduce the television image by insetting it into the appropriate location, in the radar image. Then, it could be enlarged until it filled the display. When required, the thermal image of the installation being inspected could be added. Again, an inset might be used, but, perhaps, this time it could be placed in a corner of the television image, with a marker being used to indicate the corresponding area on the television image. In this way, the battle damage assessment could be performed, using information obtained from the simultaneous display of the thermal and television images.

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The use of a single display surface could lead to improvements in several ways. The operator might accomplish the task more rapidly, or more accurately. Alternatively, it might require less effort, so that the operator has more time or energy to spend on other tasks that have to be performed at the same time. Research is needed to discover just which of the various image-combining techniques will help the operator improve his/her performance in each of the specific tasks.

We can expect new cockpit guidelines to emerge from such research. However, we should not expect them to emerge fast, nor with particular clarity at first. We are dealing with complex techniques and complex behaviors. It will not be easy to establish definitively the best way of combining images. For some tasks, one method may be optimal. But, this method may actually hinder the performance on other tasks.

SECTION III
MULTI-IMAGE PRESENTATION

There are many ways of presenting a number of images. All of them have been explored thoroughly this century, first by photographers, then, by film makers, and most recently, by television directors and editors. Anyone who wants to observe the full range of possibilities need only sit in an armchair and switch on his/her television. All of the techniques; juxtaposition, super-imposition, split screen, insetting, and variations on them, are used either in the scheduled programs or in the commercials that interupt them.

Occasionally, they are used to call attention to themselves. However, more often, they are used unobtrusively, and to become aware of them one has to pay close attention. The more common uses of multiple images are described below.

Two unbalanced, individual images may be combined to produce an aesthetically pleasing, composite image. For example, an image showing the full figure of a singer at the extreme right and nothing else in the frame, may be balanced by a second image, containing a close-up of his/her face, on the left, and looking to the right (Figure 3-1). Here, the two images are combined to produce a single aesthetic entity.

Two, or more, images may be shown simultaneously by means of a split screen, or insetting, to reveal parallel action. For example, a long shot, of the progress of the ball and action around it in a football game, may have an inset, in a corner, of a static close-up of a player injured early in the play (Figure 3-2).

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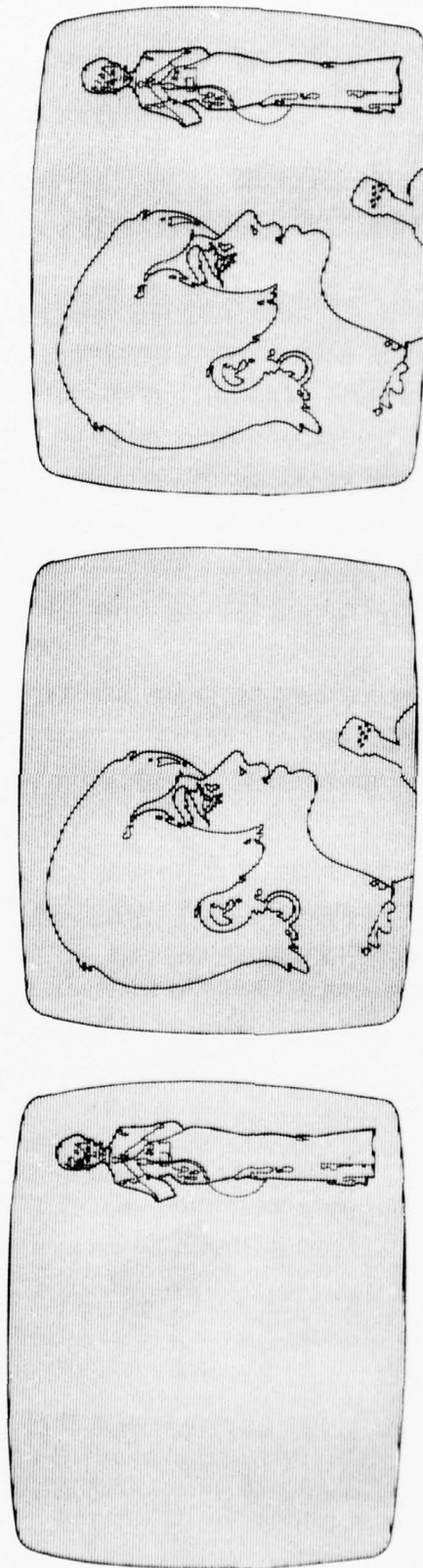
Figure 3-1. Composite Image of Singer and Close-up
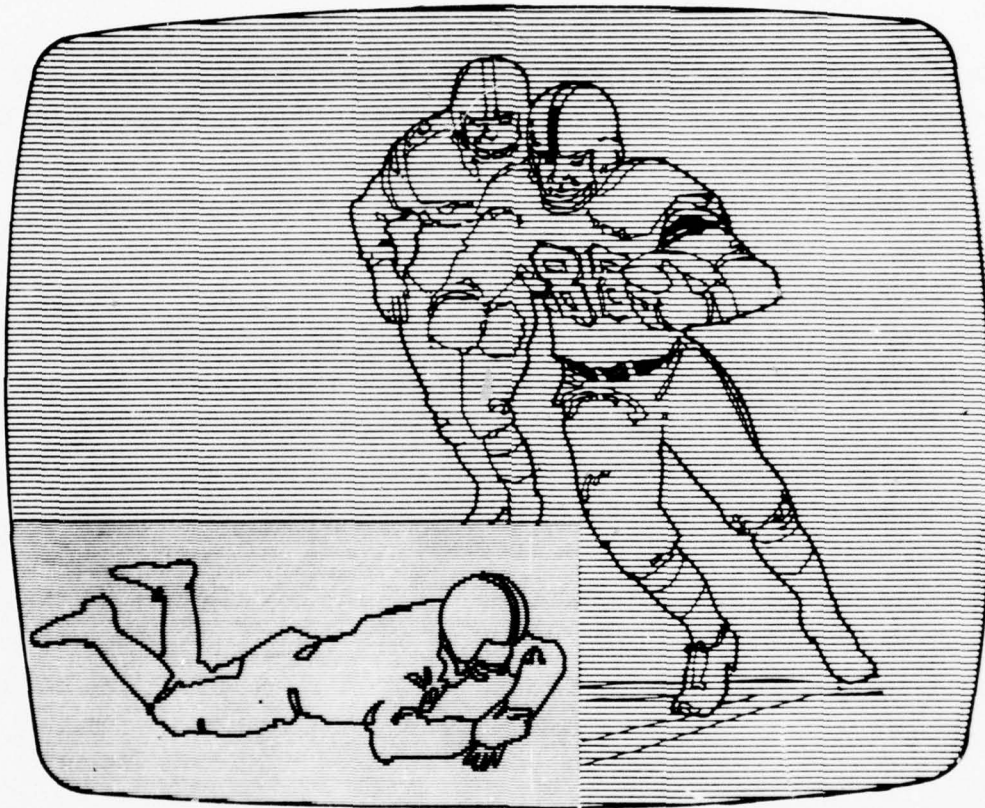
Figure 3-2. Composite of Two Parallel Activities

Most other uses of multiple images occur when the television editor, or director wants to make a transition from one image to another. The type of transition used depends on the action and mood of the particular program.

These uses of multi-image presentations are of great interest here. However, the decisions dictating their use are quite different: they are essentially used aesthetically for pictorial, dramatic, or atmospheric effects. For us, the emphasis is different. We are interested in direct responses to images. We are concerned with clarity of information and speed of assimilation.

In considering aircraft applications of multisensor displays, two kinds of problems must be addressed. The first deals with the relative effectiveness of the various ways of combining images, the second with the most efficient methods of implementing those combinations. The first of these areas is discussed in this section, while the second is dealt with in Section IV.

Before considering the potential effects of various image combination methods, it is necessary to mention, briefly, the source from which the images may emanate. It is also necessary to discuss, in rather more detail, the content of those images.

IMAGE SOURCE

Cockpit information is provided by a number of sources. As a result, we must consider several different kinds of imagery.

Low-Light-Level Television (LLLTV)

Low-light-level television systems are used mainly to provide ground information. The LLLTV camera is generally slewable, and is controlled either

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by a joystick, or by using a Helmet Mounted Sight (HMS). For most purposes, the resolution of LLLTV systems is equivalent to 600-800 TV lines.

Forward-Looking Infrared (FLIR)

Forward-looking infrared systems also provide ground information and are slewable. They can be used in two ways: first, as an alternative to LLLTV in showing terrain details; and second, with low-level temperature differences, to highlight potential targets.

Radar

Radar is typically used at a greater range than LLLTV or FLIR. The radar image has a geometry that is different than that obtained with LLLTV or FLIR. In addition, its images take considerably longer to form.

Electronic Dot Patterns/Stroke Writing

Flight data can be provided by the generation of appropriate symbols. Electronic dot patterns are used to convey alphanumeric information, while graphical data is given by stroke writing.

Film

Film can be used to give moving map imagery.

IMAGE CONTENT

It may be advantageous for a pilot or navigator to receive information from two, or more image sources. The information should be presented as clearly and concisely as possible. It is important to consider both the task that faces the operator, and the content of the images.

In particular, we must consider the relationship between the content of one image and another. There can be a wide range of relationships, from two quite unrelated images, to two corresponding images. The relationship is determined by the pointing direction of the sensors delivering the images, by the image geometries, and by the fields of view/magnifications being used. For corresponding images, two geometrically compatible sensors (LLLTV and FLIR or radar with appropriate Cartesian coordinate conversion) must be pointing at the same area on the ground, with identical fields of view. There would be less correspondence if one sensor had a narrow; and the other a wide-angle field of view; and still less, if the two sensors were not pointing in exactly the same direction, but did cover some common details. A third example of a partial relationship would be provided by combining a FLIR sensor, or LLLTV camera, and a radar directed towards the same general area.

As noted in one of the above examples, field of view is variable. Objects within it can be enlarged, and then inspected in more detail, at the cost of reducing the area covered by the sensor. With LLLTV, FLIR and radar, field of view/magnification can be changed discretely by a turret or step zoom lens. A continuous zoom lens can be used with LLLTV to provide a continuous change in field of view. This kind of transition cannot be made with current FLIR and radar systems, though for FLIR at least, it may be desirable.

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A continuous zoom lens allows two options not possible with a turret or step zoom lens. First, smooth, fluid transitions can be made with the detail of interest remaining in view and becoming progressively larger. Second, the zoom can be stopped at any point between the maximum and minimum fields of view. With the other lenses, only two or three fixed fields of view are available, and during a change from one view to another, the observer's screen goes blank.

It would be prohibitively costly to produce a continuous zoom lens for thermal image systems. However, the first of the two continuous zoom options could be provided by adding an electronic storage unit and making use of the existing step zoom lens and display. A wide-angle field-of-view image would be stored on the storage unit. Then, while the lens was being switched to a narrow field of view, there would be a continuous, electronic zoom-in on the stored image. Honeywell hopes to investigate this fake, continuous zoom effect in the near future.

Changes in field of view, whether mediated by step zoom, continuous zoom or fake continuous zoom, have a profound effect on image content. Changes in pointing angle and image geometry have similar, drastic effects. A consideration of image content is of considerable importance when one is attempting to present to an observer more than one image at a time.

USES OF MULTI-IMAGE PRESENTATION

Imagery from a number of different sources can be used in several ways.

First, an observer may need to compare the outputs of two, or more sources to derive a kind of information composite. An example was given under "Potential advantages of multisensor displays." There it was suggested that an observer might compare information gleaned from a FLIR inset, and from the marked area of a full-screen LLLTV image.

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This use is related to the first example of multi-image usage in commercial television. Here, an information composite is derived from two or more sources. There, one unbalanced image was superimposed on another to produce an aesthetically pleasing composite image.

If our first use is related to this example, our second is directly equivalent to it. In some cases, it is possible to produce an enhanced, composite image by combining separate pieces of imagery before showing them on the observer's screen. Our objective is not an aesthetic one, but rather, relates to the clarity of the resultant information.

Thirdly, the observer may need to monitor information coming from more than one source. Each image conveying information should be distinct. Our second commercial television example, of parallel action in a football game, is relevant in this case. There, parallel action was indicated by insetting, though in fact commercial television makes use of other methods, including split screen, juxtaposition in time, and (less frequently) super-imposition. We must consider these alternative methods of monitoring parallel information.

Fourthly, transitions from one image source to another may be facilitated by presenting both images simultaneously, around the time of the transition. This is similar to the third example from commercial television, although our objectives in making transitions may be rather different. We are not interested in aesthetics, drama, or mood; but in clarity and ease of understanding. As a result, a number of editing techniques will be of no use. We will not want to fade-out from our first image to darkness, and then fade-in the second one, although we may consider dissolving or mixing the two images by means of superimposition. Similarly, we will not be interested in irising-out from image to darkness and then irising-in to the new image; though again, we may think of insetting the second image in the first, and then gradually enlarging the inset. Nor will we want a turn-over, where the

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first image appears to turn over to reveal the second on its back. In this latter case, both images are distorted during the transition. However, we may be interested in using either a split screen during the image change or a wipe, in which the new image is revealed by a line that wipes off the previous image.

Some form of multiple-image presentation may be effective for each of the uses identified above. However, different forms of presentation may be needed to produce the most comprehensive information composites and the clearest composite images to convey parallel information succinctly and to give smoother transitions. We now need to consider the various methods of presentation available.

METHODS OF PRESENTING MULTIPLE IMAGES

There are several ways of presenting multiple images:

1. Images filling the whole screen may be shown simultaneously on multiple screens.

2. Images filling the whole screen may be shown simultaneously, superimposed upon each other on a single screen.

3. Images filling the whole screen may be shown separately, juxtaposed in time, on a single screen.

4. Images occupying equal proportions of the display space may be shown simultaneously on a single screen. This is known as a split-screen presentation.

5. A full-screen image may be shown with a designated portion of it overlayed by the superimposed inset of a second image.

6. A full-screen image may be shown with an inset of a
   second image replacing a designated portion of it.

7. A variant on Number 6, with the inset image placed
   in one corner of the main image, and a marker indicating
   an area of special interest in the latter.

8. A variant on Number 7, with an inset again placed in a
   corner of the main image. In this case, there is no
   marker, as there is no special relationship between the two
   images.

MATCHING METHODS TO USES

We have described eight different methods of presenting multiple images,
and four main uses of such a presentation. The next step, is to discuss
which method, or methods, might be most appropriate for each use. Table
3-1 lists the various methods and uses. An indication is given of those
methods that are inappropriate for some uses, those that may be useful,
and those we judge to be most promising.

It should be noted that Table 3-1 presents judgments. An experimental
investigation is required before any definitive matches of methods and uses
can be stated.

The table is discussed in terms of the four identified uses of multiple-image
presentation.

Table 3-1. Applicability of Eight Methods of Presenting Multiple Images to Each of Four Ways of Using Those Images. (Key: X = Inappropriate; P = Possible; M = Most Promising)

Methods	Uses			
	Information Composite	Composite Image	Monitoring Parallel Information	Transitions
1. Multiple Screens	P	X	P	P
2. Full Image Superimposition	P	M	P	P
3. Juxtaposition in Time	M	P	M	M
4. Split Screen	M	X	M	P
5. Superimposed Inset	P	M	X	X
6. Inset (Replacement)	X	M	X	M
7. Inset with Marker	M	X	X	P
8. Inset, No Relationship	X	X	M	P

Information Composite

In this use, the observer has to construct a composite of the information he/she extracts from two or more distinct image sources.

All three methods using full-screen images could be used. With Method 1, multiple screens, the distance between the displays showing the imagery should be the minimum. The farther apart the relevant displays happen to be, the larger the eye movements needed to look from one to the other, and the less satisfactory this method is likely to be.

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Method 2, involving superimposed full screen images, could be used. However, some coding of the images, perhaps by color, would be necessary if they were to be easily distinguishable from each other.

The third full-screen method is more promising. Observers may find they are able to combine information judiciously, when it is derived from images that are shown alternately on a single screen. Several questions need to be investigated: should the observer control the alternation process? Is there an optimal alternation rate? Does optimal rate vary with image content?

Method 4, split-screen presentation, also may be appropriate for this usage. It is similar to multiple-screen presentation, but has at least one advantage. Since the images are presented side by side on a single display, inter-image distance is at a minimum. This method will be suitable, if there is sufficient resolution on the half-screen images to see the details of interest clearly.

Two of the four methods involving insets are inappropriate for this usage. Method 6, in which the area of interest in the full image is replaced by an inset, is clearly unsuitable, since no comparison would be possible. And, in Method 8, since there is no special relationship between the inserted image and the full image, no comparison could be made.

Method 5, in which an inset is superimposed, might be useful. As with full-image superimposition, coding would be necessary, or the inset may simply merge into the full image.

The last inset, Method 7, joins Methods 3 (juxtaposition in time) and 4 (split screen), in having the most potential for this use. In this case, the area of interest on the full screen is marked, and an inset shows the area via another sensor system. Resolution is less likely to be a problem than in the split screen method since the area of interest can be shown with a maximum resolution

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on both inset and full screen. In addition, unlike either the juxtaposition in time or split screen methods, the details for comparison can be pinpointed more accurately.

Composite Images

In this case, the observer receives a single image that is a composite of two, or more, combined images.

Methods 1 (multiple screens), 4 (split screen), 7 and 8 (both with insets in the corner of a full image) are all clearly inappropriate.

Method 3, juxtaposition in time, is a possibility, but only because of a technicality. If the alternation rate of two distinct images is sufficiently rapid, the two images appear to be superimposed upon one another. If a suitable rate were used, a composite image would be seen. However, if alternation were used in this way, it should really be considered as an alternative way of implementing superimposition Method 2.

The two superimposition methods, with full images (Method 2) and with an inset (Method 5), are clearly of great interest here. However, there may be problems in balancing the images that are to be combined. First, misalignment of the images could lead to interference that would degrade each image. Second, the gray scale, or dynamic range, of the individual images should be matched, otherwise the display with the larger dynamic range would dominate the other(s). Third, the signal to noise ratio in the images needs to be balanced, since a high noise content in one image would degrade information from another. These technical problems need to be dealt with if this form of image enhancement is to be conducted in real time.

Spotlighting is a special case of superimposition Method 2. Here, the low temperature differences picked up by the FLIR sensor would be supressed. Then, the high temperature differences could be used to indicate potential targets. The FLIR image might be defocussed slightly, so that it did not interfere with the detail information contained in a LLLTV image. The latter would be used to identify targets from amongst the candidates suggested by the FLIR.

One last method needs to be discussed in relation to this usage: Method 6, involving an inset that replaces a portion of the full image. In this case, the observer may need to combine terrain background information, perhaps from a LLLTV, with a small inset of FLIR target information. The FLIR sensor might be used by the observer to search around the LLLTV image. There would be no alignment problem, nor would it be necessary for both sensors to have the same scale.

Monitoring Parallel Information

In this use of multiple image presentation, the observer's task is to monitor information coming from two or more sources continuously. Each image needs to be distinct. There are similarities between this case and the first usage involving an information composite. In both cases it is necessary for the images to remain clearly distinguishable from each other.

As before, the three full-screen methods could be used. With a multiple-screen presentation, the inter-display distance should be as small as possible. With superimposition, coding would once more be needed to ensure that the images are distinct. And again, alternation in time is the more promising method, with a similar investigation into alternation control and rate being called for. Method 4, involving split-screen presentation, would again be an appropriate method.

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There are differences between the two usages that emerge when we consider the various insetting methods. Those methods (5, 6 and 7) that deal with ways in which the inset image is related to the full-screen image are all inappropriate. Only Method 8, in which an unrelated image is inset in a corner of the main image, is revealed as a candidate.

Transitions

In making transitions from one image to another, a number of multiple image presentations may be useful. In fact, of the eight methods that were identified, only one can be eliminated. There seems to be little point in using Method 5. The combination of superimposition and insetting is unlikely to ameliorate transitions, although either alone could be of assistance.

With multiple screens, transitions would be mediated by eye movements from one sensor display to another. This method seems unlikely to be the best, although it may be as good as Methods 2 (superimposition), 4 (split screen), and 7 (inset placed in one corner, with marker in the area of interest), and it is probably better than Method 8 (where an unrelated image is inset in a corner of the full screen image). It may also be as useful as one commercial television editing technique that was not covered by our listing of methods of presenting multiple images. This technique is the wipe. In this, one image is swept away by the leading edge of the second image.

The two most promising transitional techniques are Methods 3 and 6. The former, juxtaposition in time, here becomes direct-cutting. The latter, with an inset replacing a specific area of interest, may be particularly useful in target acquisition operations. After the image was inset, the transition would be effected by allowing the inset to grow gradually until it filled the whole scene, and had completely replaced the initial image. There are

two ways that the inset image could be expanded. Either part of the second image could be inset, and the rest revealled gradually. Or the whole of the second image could be minified, inset, and then magnified and centered on the display. The latter is rarely seen and harder to implement, but may be interesting for our purposes.

While discussing transitions, changes of field of view involving a single sensor should be mentioned. When a turret, or step zoom lens is used, the observer's display goes blank during the transition from one field of view to another. This may result in some disorientation or confusion. It may be difficult for the observer to decide exactly what is in the narrow field of view, and/or how it relates to the previously visible, wider angle view. These potentially disconcerting effects may delay the observer's response. The delay may only be short. Nevertheless, for tasks such as target acquisition, it may be of considerable importance.

It is possible that the use of a real, or fake continuous zoom lens system would avoid such effects and lead to a more efficient performance.

RECOMMENDATIONS

There are 32 combinations of presentation methods and presentation uses listed in Table 3-1. As the table and the subsequent discussion show, 10 of these combinations can be eliminated from further consideration. However, 22 combinations seem to have some possibilities. Of these, 11 seem particularly promising. With the exception of the multi-screen method, all seven remaining methods, i.e. all methods involving a single screen, seem to be promising in at least one usage. Because of this, we will discuss ways of implementing each of these methods in the next section.

SECTION IV
IMPLEMENTATION

INTRODUCTION

Any airborne multifunction display must be able to present information from
a variety of sensors and data sources. The multifunction display must not
only be compatible with various sensors but also with computer-generated
symbology derived from instrumentation sensors and/or weapon systems.
The input sources which appear to require the highest performance from an
airborne display are those which form images. The inherent flexibility of
electronic displays such as the cathode ray tube is particularly attractive for
multifunction use. While the inherent flexibility permits a high degree of
optimization to a specific system under specific viewing conditions, obviously
a multifunction display has a large range of performance requirements and
presents a formidable task to the display designer.

A representative list of sensors and other data sources for a multifunction
display on a military aircraft includes the following:

Low light level TV (LLLTV)

Forward looking infrared (FLIR)

Radar

Computer generated and processed information (e. g. ,
weapon aiming, flight information, and aircraft systems)

Dedicated electronic cockpit displays have been in use for many years. But
with current proliferation of sensor systems and increased quantity of pro-
cessed data available from digital computing systems, a need exists to mini-
mize crew workload within instrument panel space. The optimal approach

to design of an integrated, multisensor, multifunction display system seems to be a raster based integrated display system. In it, all sensor data are converted to the standard video line rate prior to mixing with any synthetically generated symbology. Various approaches to combining sensor imagery with synthetic symbology will be discussed in this section.

It is unlikely that the resolution and gray scale requirements for radar information will exceed that of the optical image forming sensors; hence, it will not represent a limiting condition on display performance. It is unlikely that symbology for target designation or navigational data for flight information would define the limiting conditions for a multifunction display. Rather, it would need to be compatible in readability, contrast, accuracy and resolution with associated imaging sensor information.

The radar sensor is basically incompatibility with a multifunction (TV raster) display due to its relatively slow scan rates. A radar sensor requires either a display with a long persistence or some sort of scan conversion to display the imagery at TV refresh rates.

Two types of synthetic symbol generation are stroke writing and raster writing. Stroke writing is produced by applying analog x and y signals to the x and y deflection circuits of the display device, causing the spot to deflect on the CRT face correspondingly. The spot is switched OFF while it is being moved into position and ON while it is being moved to create a line or symbol. Raster writing (as in television) is produced by generating x and y triangular waveforms locked to the synchronizing signals from the source in the x and y deflection circuit of the display device. Triangular waveforms cause the spot to trace out a large number of horizontal lines. The brightness of the spot is varied to generate the symbol as horizontal lines comprising it reach the desired location on the screen.

A display designed originally for raster writing cannot easily be modified to generate stroke written symbols. However, a stroke writing display can usually generate raster writing without modification.

The TV raster approach has the advantage of being cost effective with low power requirements. However, the stroke writing display has the capability of generating high resolution symbols between fields of the standard TV display format. When this is done, the symbol brightness adds to the brightness of the raster imagery, and the synthetic data are always legible. In other words, the symbol becomes whiter than the white of the image in the raster. Raster type displays must use some techniques such as black bordering for the synthetic symbol to be visible against peak white portions of the scene. However, this obliterates some of the imagery. Conflicting results of various optional design approaches must be traded off against requirements of the specific aircraft's mission.

A detailed analysis of proposed image combining techniques has not been undertaken in this study. A meaningful analysis of MTF, resolution, brightness, contrast, visual acuity, probability of detection, recognition, and identification requires the definition of a specific sensor/combiner/display system for a specific application. Therefore, it appears that the most cost-effective approach to the multifunction display problem is to select a candidate from the alternatives in this study on a qualitative basis. A follow-on effort should then be implemented to perform a quantitative analysis of its suitability to its specific application and aircraft.

The main thrust of this study has been directed toward the standard television monitor. Advantages of this display type are high resolution and high brightness when combined with a narrow band phosphor and matched spectral filter for visibility under high ambient light conditions. The television monitor's tuned CRT display has the advantages of simplicity, reliability, maintainability, lower power and low cost as compared to other types of displays. Before adopting it, however, a very important tradeoff in display design is required between the number of symbols and the ability to write them during the field fly-back time of the raster display. This tradeoff is among the display brightness, the writing speed, and the number of symbols to be imaged.

In addition to raster and stroke-written CRTs, other display materials will be discussed. These include plasma panels, light emitting diode arrays, electro-luminescent panels and liquid crystal panels. This study is primarily concerned with the heads down display rather than the heads up or helmet-mounted display, though some image combining techniques discussed here also apply to them.

SYSTEM REQUIREMENTS

Table 4-1 summarizes the requirements on which the analysis of various image combining techniques is based. These requirements do not relate to a specific application but have been selected to reflect a generic worst case for a multifunction display. We assume the sensors have high quality imagery with EO sensors having a TV compatible video output. Five cases for image combinations have been selected. We assume also that the radar and moving

Table 4-1. Preliminary Requirements for Candidate Image Combining Concepts

Sensors

- High-quality radar with forward sector PPI coverage at slow frame rates and low number of gray shades.

- High-quality forward oblique FLIR and LLLTV at high frame rates and high number of gray shades.

Annotation

- Moving map

- Symbols and graphics

Image Combination Cases

- Radar and moving map sequentially or simultaneously at same scale.

- Sequential or inset radar imagery into E-O imagery. Radar imagery is at a different scale and geometry.

- FLIR imagery insert at different scale and geometry into LLTV imagery or vice versa.

- Combine FLIR and LLLTV imagery sequentially or simultaneously at same scale and geometry.

- Symbol and graphics annotation for both radar and E-O imagery.

Cockpit Environment

- High ambient illumination

- Limited head motion requirement

- Severe vibration

Display (Design Goals)

- Pilot - 11.4 x 14 x 28 cm with 10.8 x 8 cm active area. (525 TV lines)

- Navigator - 21.6 x 17.1 x 41.2 cm with 18 x 13.4 cm active area. (875 TV lines)

- Viewing distance - 51 to 76 cm.

Tasks

- Aircraft flight control: Orientation, terrain following and avoidance, trail following, threat avoidance, rendezvous, approach and landing.

- Navigation: Orientation and checkpoint location, checkpoint designation and position entry for navigation update.

- Attack: Target detection, recognition, classification, identification, location, designation, position entry and tracking.

Design

- Simple

- Reliability

- Low cost

map imagery have the same scale and geometry. No requirement has been assumed to present the radar and EO imagery at the same scale and geometry. The radar is assumed to have a forward looking PPI format. The EO sensors are assumed to have a forward oblique geometry but can be at different scales, geometries or TV line rates. Symbol annotation is assumed for both radar and EO imagery.

A cockpit environment with a high ambient illumination, limited head motion and severe vibration (as in a helicopter) is assumed. Air crew tasks are assumed to be fairly complex and require high-quality radar and EO imagery. Design goals for the multifunction display are high reliability, simplicity, low cost and a minimum cockpit space.

SENSOR, DISPLAY AND IMAGE COMBINING COMPONENT CHARACTERISTICS

Sensors

Radar -- A forward-looking PPI sector, slow scan radar has been selected as one of the imaging sensors. A worst case for displaying information has been selected that assumes a good quality ground map image and a requirement that the operator recognize the target. These requirements impact the type of display that can be used. A typical forward-looking radar requires about one second to form a complete image. It demands, therefore, that the display system store the image over that time if the air crew is to see it in its entirety. A television sensor takes only one-thirtieth of a second to form a complete image, and television information will be lost if it is stored for one second. Consequently, some sort of scan conversion must be used for

the radar sensor to convert it to TV compatible video. Studies of operator performance indicate that eight shades of grey ($\sqrt{2}$ ratio) are adequate for radar imagery, and at least 16 are needed for EO imagery[1]. It is unlikely that resolution requirements for the radar display will exceed the resolution requirements for an EO sensor. Hence, radar imagery does not represent a limiting condition for display performance[2].

Forward-Looking Infrared Sensor (FLIR) -- We assume that the FLIR sensor, whether serial scan or pushbroom type, will have output video in TV compatible format. The field of view of the FLIR sensor ranges from 65° for navigational systems to about 4° for target identification and tracking systems. Current spatial resolutions are about 0.2 mrad, which requires 350 resolution elements across the four-degree, narrow field of view. Gray scale requirements are about 16 shades of gray for the high-quality imagery assumed for this study. The ground footprint of the forward oblique field of view of the FLIR sensor presents an image with a varying ground resolution from the bottom to the top of the display. Therefore the FLIR image geometry is not compatible with the cartesian ground presentation of the radar sensor.

Low Light Level TV Sensor (LLLTV) -- Numerous LLLTV systems are available from various combinations of camera tubes and intensifiers. Under reasonable light levels, these systems have a resolution of between 600 to 800 TV lines per picture height. Consequently, the LLLTV systems with a 16 gray scale requirement represent the worst case for display requirements.

Symbol Generator

An electronic display system must be capable of generating a variety of symbology and superimposing this on a picture of the outside world provided by the FLIR, LLLTV or radar. An example of symbology for a system without imagery is shown in Figure 4-1. Here (in the A-7 aircraft) symbology is

33
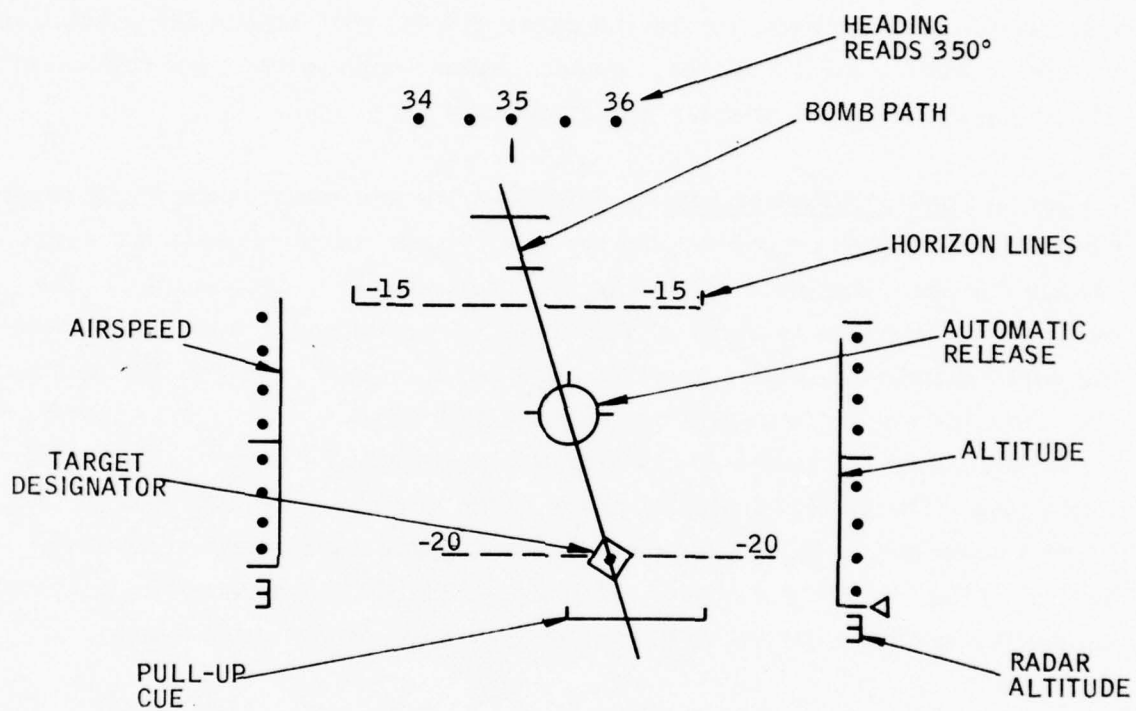
Figure 4-1. A-7 Weapon Delivery HUD

presented to show target designation, automatic release point and the bomb path. The display also shows the air speed, pull-up cue, radar altitude, horizon line and heading. Figures 4-2, 4-3 and 4-4 show F-16 displays combining weapon delivery vectors with FLIR or LLLTV imagery. Figure 4-2 shows the weapon status for the continuously computed impact point and bomb fall line and velocity vector. A dive toss mode is shown in Figure 4-3 against a bridge, and Figure 4-4 shows the gun or rocket steering line and gun rounds remaining against a truck target.

A typical symbol display system configuration is shown in Figure 4-5. The symbol generation facility consists of three main units--a computer, a wave form generator and interface unit. The interface unit receives signals from various aircraft data sources and directs them to the computer, which calculates parameters of the display symbols. These parameters are in turn fed to the waveform generator. The FLIR or LLLTV and its associated control unit supply the video to the waveform generator, which mixes it with symbology to produce a composite video waveform[3]. This system is a raster-based electronic display that mixes the symbology with the raster of the sensor imagery.

An alternate procedure is to replace the waveform generator with a display processor that generates signals to stroke write on the display. This requires a direct drive display system. Symbols in the stroke write mode are usually written in the flyback time between fields of the sensor signal. The number of symbols that can be written in the fixed flyback time is directly proportional to the speed of the deflection circuits and inversely proportional to the required brightness. The writing speed or rate can only be improved by increasing the deflection circuit's bandwidth and power.

Several computer/display command interfaces are possible. The easiest for the display but the most time consuming for the computer is a point-by-

Figure 4-2. F-16 Continuously Computed
Impact Point (CCIP)

Figure 4-3. F-16 Dive Toss

Figure 4-4. F-16 Gun/Rocket
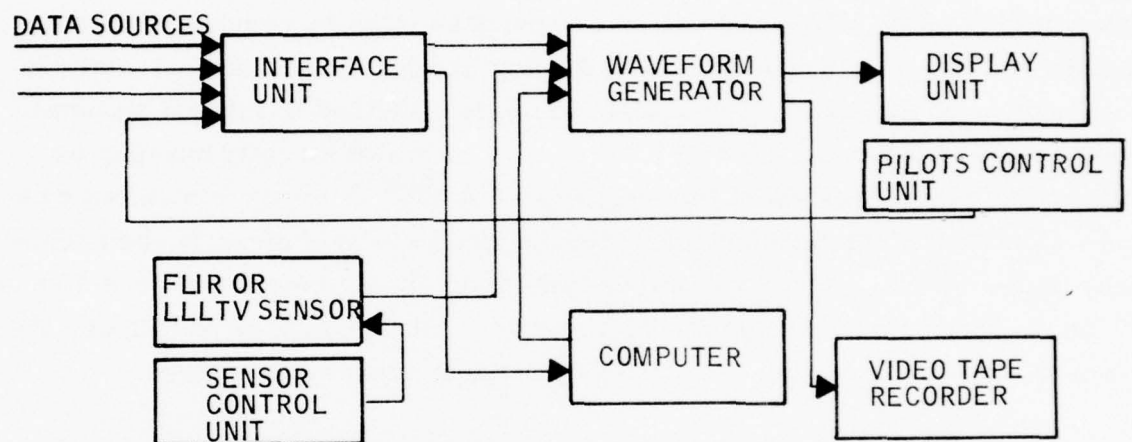
Figure 4-5. Display System Configuration

point method where each picture element is addressed sequentially by the computer. Another method, requiring less computing power, uses a display device that can draw predetermined objects in specific orientations and the computer only specifies that location. This limits the flexibility of the display significantly. Somewhere between these two levels of complexity is the line orientated display. Here the computer specifies lines as vectors with initial coordinates, angles, and lengths; the display hardware does the calculations necessary to draw them. The restriction in this method is that all pictures must be line segments. Curved lines cannot be drawn directly but may be approximated by many short line segments. A CRT is easily controlled by a line-orientated display generator. High-speed deflection circuits are necessary in the CRT to allow all required lines to be drawn before the persistence of the phosphor requires them to be redrawn. This method of positioning the beam to arbitrary location is known as a random scanning technique.

The standard television monitor utilizes a fixed raster scan technique. With this method the position of the trace cannot be selected by the display generator. Scan positioning the electron beam is a known function of time. Only the intensity can be controlled externally. To draw a line, all points through which the line passes must be known and constantly compared with the actual location of the beam. When they correspond, the beam is unblanked. This method works well when only horizontal or vertical lines need to be drawn. However, the appearance of diagonal or curved lines is uneven or ragged due to the step-wise construction. The random scan displays are preferred when short curved or diagonal lines are required.

Moving Map

Current moving map displays have a high resolution projected map image obtained by using film cassettes, servo drives and special optics. The map imagery is usually superimposed on CRT-generated symbols and a CRT-

generated navigation radar image. Usefulness of the radar image and map display is greatly enhanced if they are accurately registered. One technique for combining these images uses a rear port CRT as shown in Figure 4-6. This particular configuration was proposed by Control Data for the Boeing B-1 system[4]. The film is scanned by a rotating periscope as shown in Figure 4-7. Rotation of the map imagery is accomplished by orientation rotator optics; examples are shown in Figure 4-8. The rotating periscope scans the film in the North/South direction, and the combination of the rotating periscope and film motion scans the film in the East/West direction. This particular system contains a hundred feet of 70-millimeter film with three magnification scales, as shown in Figure 4-9. The performance summary in Figure 4-10 indicates a limited brightness of 500 foot-lamberts, which is typical of a rear port CRT system.

The fundamental problem in this approach is that the phosphor must be reduced in thickness when a CRT is used as a back projected screen. The brightness level of a radar image may then be inadequate under high ambient illumination conditions.

The Control Data CDS-1 system employs contast enhancement techniques that include a fiber optics face plate, a neutral density filter and antireflection coatings. A field lens may be used for extremely narrow viewing lobe applications. Even with these techniques, visibility of the combined image in the presence of high ambient lighting condition may not be satisfactory. An alternate approach, shown in Figure 4-11, combines the electronic CRT and projected film images at a combining glass. An important advantage of this approach is that the two images can be separately enhanced before combination. The CRT image is monochromatic (P-43 green phosphor) and is enhanced by using a narrow band pass filter over the CRT face. The film image is fully chromatic and is enhanced by using a high contrast screen material in conjunction with a circular polarizer. Antireflective coatings are used throughout. The result is a full-color map readable under high ambient

CONTRAST ENHANCEMENT
ELEMENTS

PROJECTION LENS

PHOSPHOR

OPTICAL PORT
AXIS

CRT AXIS

OPTICAL
ROTATOR

OPTICAL
PORT

CRT OUTLINE

FILM SPOOL

DEFLECTION YOKE

CRT GUN

CONDENSER

LAMP AND
REFLECTOR
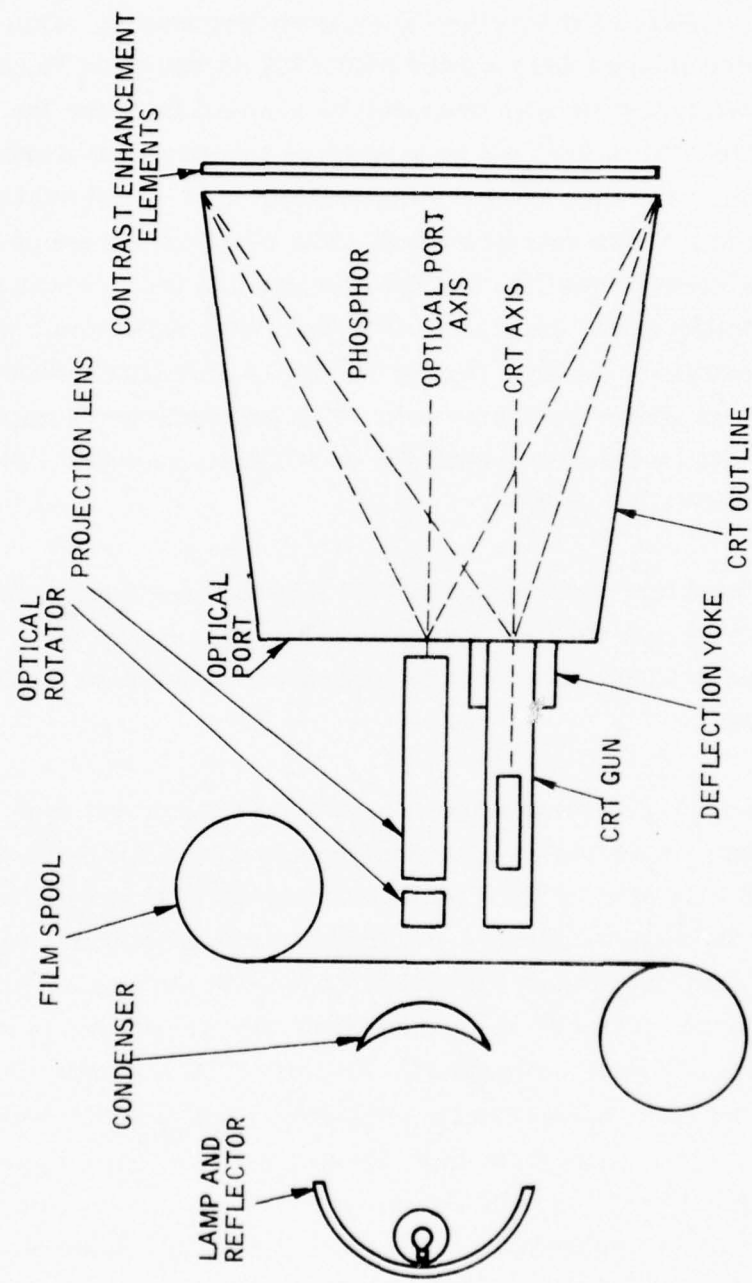
Figure 4-6. Combined Map and CRT Display

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Figure 4-7. Film Scanning

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RANTSCH ROTATOR

PECHAN

COLLIMATING
LENS

DOVE
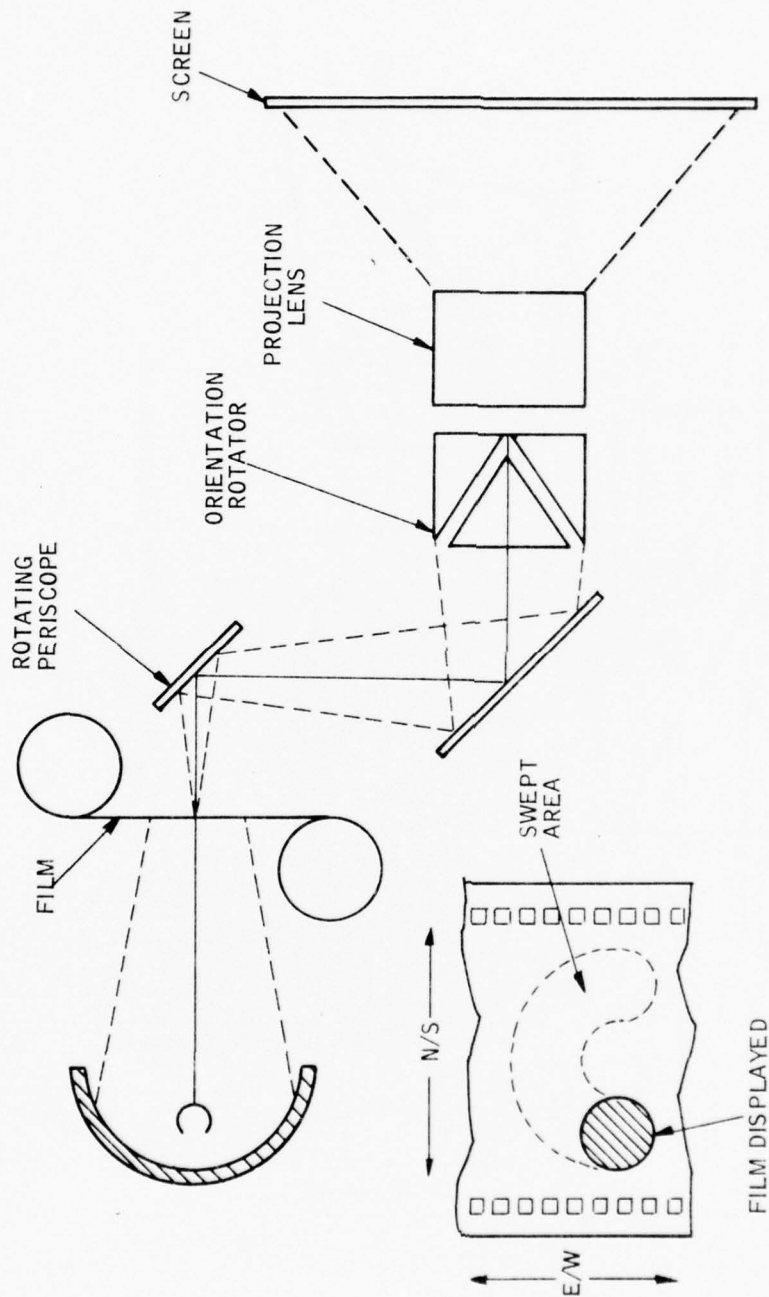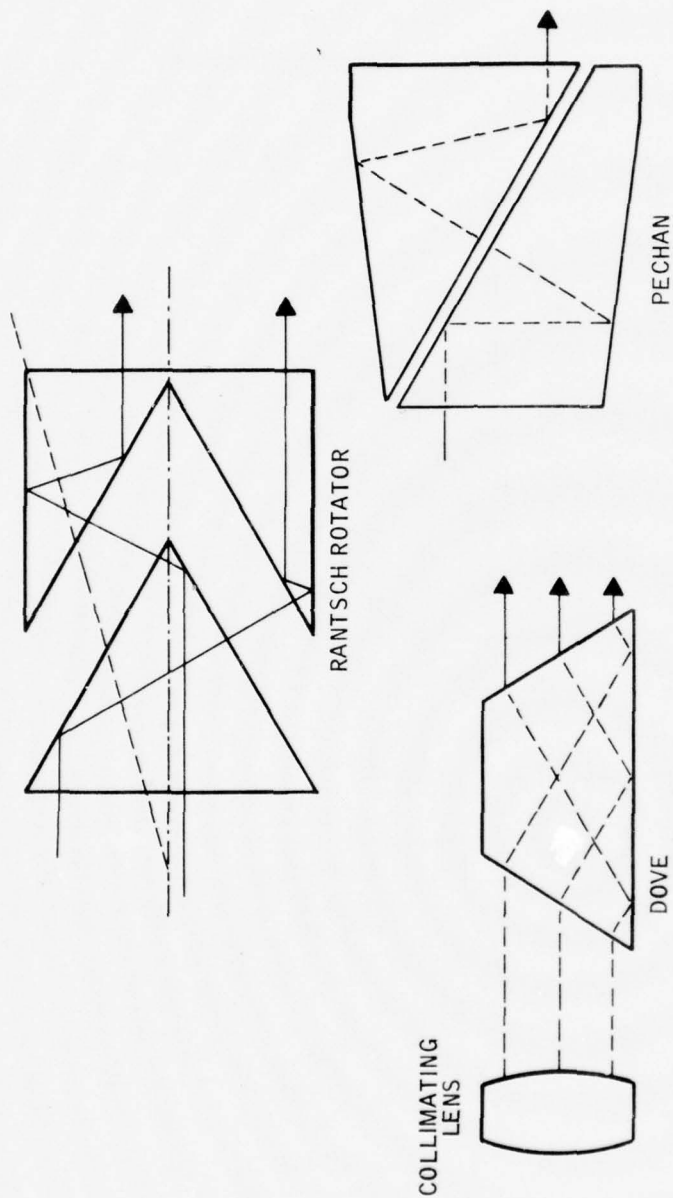
Figure 4-8. Map Rotational Techniques

42

2.40"
BETWEEN
SPROCKETS

70 MM

HYSTERESIS
(ABOUT 0.075")

USEFUL
WIDTH
(1.70")

FILM GATE
(0.625" DIA)

OVERLAP
0.625" NET.
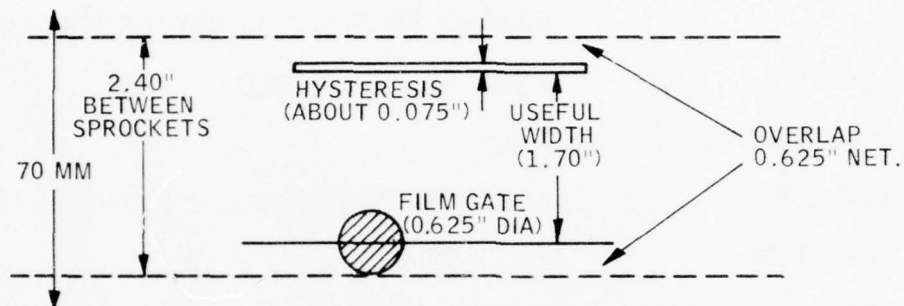
EQUIVALENT WIDTH ON CHART = 1.70 X 12/1.3 = 15.7 IN. (30% OVERMAG.)
EQUIVALENT CHART AREA 1200/1.3 X 15.7 = 145,000 SQ. IN. (382 X 382 IN.)
COVERAGE EXAMPLES:

SCALE	SCREEN DIA.	GRID COVERAGE	STRIP COVERAGE
1 : 2 M	157.6 NMI	10,500 X 10,500 NMI	430 X 25,000 NMI
1 : 1 M	78.8 NMI	5,240 X 5,240 NMI	215 X 12,600 NMI
1:1/2M	34.4 NMI	2,620 X 2,620 NMI	108 X 6,300 NMI

Figure 4-9. Film Coverage

PROJECTED MAP

AREA -   MASKED TO 7-1/2 IN. DIA. CENTRAL AXIS

BRIGHTNESS -   > 500 fL UNFILTERED

MAGNIFICATION -   12X

ACCURACY -   < 0.05 IN. POSITIONAL; < 1° ARC ROTATIONAL

RESOLUTION -   > 6 LP/MM

FILM -   100 FT. 70 MM

CRT (P31 PHOSPHOR)

AREA -   10 x 7-1/2 IN. (IN 12-1/2 x 12-1/2 x 26 IN. UNIT

BRIGHTNESS -   STROKE SYMBOLOGY > 300 fL   UNFILTERED
                     875-LINE RASTER   > 85 fL AVG

VIDEO GREY SHADES - 6 LOGARITH. SHADES AT 100 FC
                     12 LOGARITH. SHADES AT 10 FC

LINE WIDTH -   0.012 IN. (SHRINKING RASTER)

ACCURACY -   0.09 IN. RELATIVE TO MAP

Figure 4-10. Performance Summary

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MAP IMAGE

HUD AND
CONTROL
PANEL

COMBINED
IMAGES

LENS

ROTATOR

COMBINER

LAMP

CRT IMAGE

FILM CASSETTE

POWER SUPPLY

PCB'S
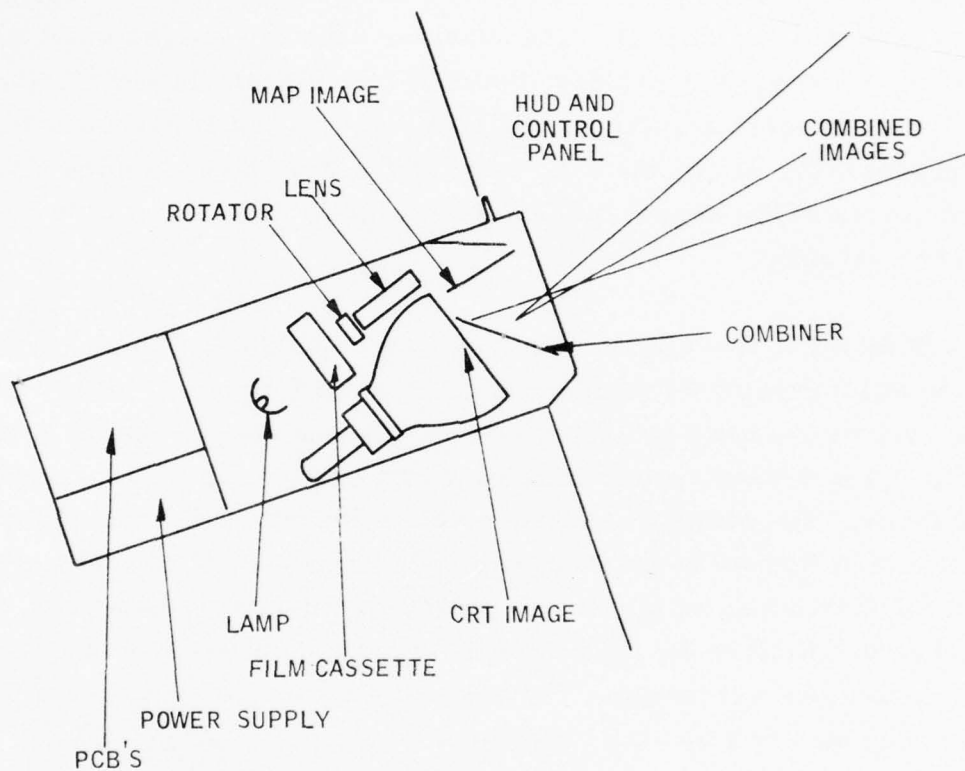
Figure 4-11. HSD Simulator Display Unit

illumination. The combined image is real, not virtual; and allows considerable freedom of head movement for the pilot or observer.

The CRT and map image planes are spaced optically equidistant from the beam splitting mirror surface. The observer sees two images which appear to be combined at one image plane, the CRT face plane. This particular CRT presentation has a rectangular format 15.2 cm high and 13 cm inches wide and is proposed for use by the U.S. Navy on the F-18 aircraft simulator[5]. The dimensions of the display unit are estimated to be 17.3 cm wide by 26 cm high and 51 cm long.

The disadvantage of this approach is that direct sunlight can impinge on the CRT face and the map projection screen, reducing the display contrast. The alternate approach shown in Figure 4-12 overcomes the problem by presenting the image via a viewing system consisting of a combiner mirror, transfer lens and field lens. The combiner mirror reflects the real map image (from the rear projection screen) and transmits the CRT image such that they appear superimposed in the same plane. To prevent paralax, it is important that the relative positions of the CRT screen, projection screen and combiner all be held to close tolerances. The exit pupil of this particular system[6] is 19 cm in diameter at a viewing distance of 66 cm. This allows a vertical head movement of plus or minus 9.5 cm and a horizontal head movement of about ±6.3 cm, depending upon the interpupilary distance of the operator.

The field lens viewing system has several important advantages over the system shown in Figure 4-11. Note that the transfer lens focuses a real, combined image at the position of the field lens. The observer then sees the real image in the field lens and the lens directs the diverging light from the transfer lens to the exit pupil for increased brightness.

The advantages of this system are several. First, direct sunlight cannot enter the system to reduce the contrast of either the map or CRT images.
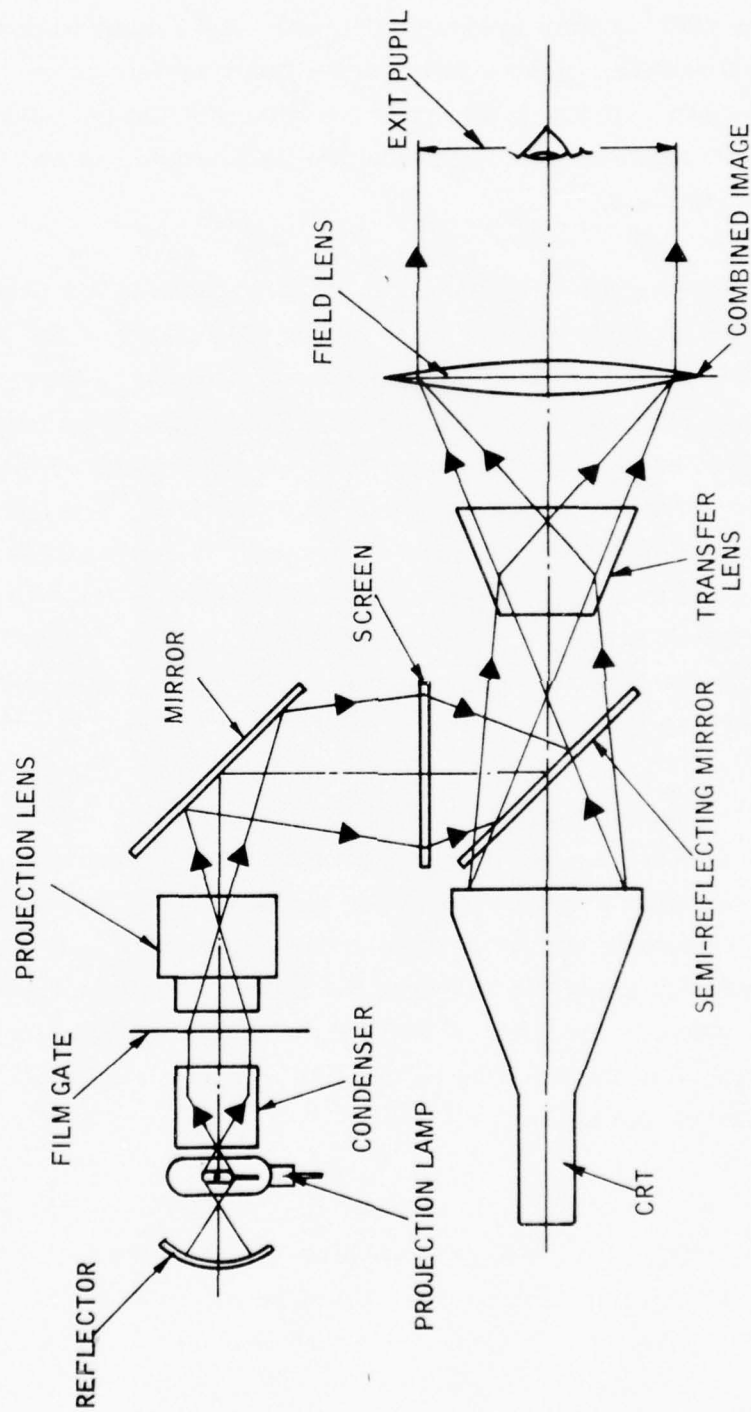
Figure 4-12. Combined Display Optical System

To impinge upon the CRT or map projection screen, light must pass through the transfer lens. However, to pass through the transfer lens it must also pass through the system exit pupil, which is the image of the transfer lens exit pupil. This is impossible since the exit pupil's diameter is completely filled by the operator's head.

Second, the display has higher brightness. The brightness of the primary image (as seen by the operator) is the same as the brightness of the source, i.e., the map projection screen and CRT phosphor. However, these images are almost five times brighter (due to 2.2 times image magnification) than if full sized images were used. This assumes that the brightness of the map projection screen is inversely proportional to its area, i.e., 6.9 cm map screen diameter instead of a 15.2 cm map diameter. The brightness of the 7.6 cm CRT used in the system has twice the brightness of a 15.2 cm diameter CRT for equivalent drive powers. However, a 7.6 cm CRT has four times the brightness of a 15.2 cm rear port CRT since rear port CRTs cannot have aluminized screens.

This particular system accommodates 17.37 m of 35 mm film. This is equivalent to an area of 366 km by 366 km with a film-to-screen magnification of 7.5 times and a chart-to-film reduction factor of 15. This system has an access time of 10 seconds and the ground area is split into E-W strips photographed sequentially along the length of the film. Different scales are located on different parts of the film, permitting a variable magnification. The accuracy of synchronizing the map to the CRT images is approximately one percent anywhere on the screen(Ref. E).

All moving map systems accept a manual initialization to the approximate aircraft location and heading. The projected map image can then be compared to the radar map image for updating. When the map image is in manual registration with the radar map, the map drive control can be switched over to automatic update by the aircraft digital navigational control. These systems are capable of selecting scales to match the radar map.

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Displays

Aircraft Display Requirements and Display Types -- The primary require-
ment for any cockpit display is that it must be legible under high and low
levels of illumination, as well as in darkness, and to pilots of all age groups.
Illumination levels in direct sunlight can be as high as 10^5 lm/m^2. Increased
reliability and ruggedness beyond that typical of incandescent lamps and
electromechanical devices is sorely needed.

It is also desirable for displays to have a graphic (line-drawing) capability
and be able to show alphanumeric characters and symbols without a large
number of wires connecting the display to the drive electronics. Aircraft
displays must also be compatible with modern integrated circuits and should
operate on low voltage aircraft power. The display should also operate over
a minimum temperature range of -20° to +70°C.

Displays may be classified into one of two types: passive displays, which
function by modulating ambient illumination; and emissive or active displays
which generate light. The following paragraphs briefly describe promising
examples of both types and give their general characteristics; more technical
details are supplied in Appendices I through P of reference 7.

The introduction of on-board computing systems means that more sophisticated
displays can be made available. For example, an on-board computing system
can directly indicate through the display the estimated time of arrival at any
particular point instead of requiring the pilot to read several dials and per-
form a calculation. Displays can also present navigational information, data
on the mechanical state of the aircraft, and results of any automatic checks
carried out by the calculator. It is quite possible that one or more larger
displays may be used to perform these functions, reducing the cockpit area
taken up by instrumentation.

Contemporary electromechanical instruments are bulky, require large panel areas, and are undesirably heavy. They also have a relatively slow response, contain moving parts, and may be sensitive to vibration. The only other display technique commonly used is the cathode ray tube (CRT); however, CRTs are rather heavy and bulky, require a high voltage, and carry a slight risk of implosion.

Characteristics of Passive Displays -- The advantage of reflective, passive displays is that their contrast is independent of the illumination level, i.e., they modulate the ambient light. This modulation is controlled on individual elements to form the desired image. They consume little power and are ideal for large displays. A difficulty with passive displays is material saturation with increasing drive voltages. It is impossible for the passive display to compensate for the necessary short-address period by driving the display harder at higher voltages. To fill this need, some form of either inherent (in the form of high decay-time/rise-time ratio) or on-site memory must be employed.

Passive displays also require some illumination for night viewing and their field of view may be limited. An additional possible disadvantage in airborne application is a degradation of contrast in diffuse illumination, i.e., flying through a cloud, for those displays based on a scattering mechanism.

Characteristics of Emissive Displays -- Light-emitting displays are less critically dependent upon the color, reflectivity, and position of surrounding objects than reflective displays and are more easily read in low ambient lighting conditions. However, they must have sufficient luminance to compete with ambient illumination (up to 10^5 lm/m^2), must be visible when the eye is adapted to luminance levels up to 3.4×10^4 lm/sr/m^2 and must have adequate contrast with the immediate surrounding cockpit area.

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Several techniques are available to reduce the amount of ambient light reaching the display. Bezels can be used where a limited field of view is acceptable and the space available. More compact methods restrict the range of incident light on the display through the use of louvered plastic or imbedded mesh filters. Alternately, neutral density, colored, or circularly polarizing filters can be used. The colored filter matches peak spectral emittance of the display. All filters attenuate the incident ambient illumination twice while they attenuate the emitted display light once, resulting in improved contrast.

One important advantage of the emissive display is an unsaturated output. The emitted light increases in proportion to the drive voltage up to a relatively high level. However, the display luminance must be reduced as emitted display light that is bright enough under high illumination conditions will be too bright and, therefore unreadable at low luminance levels. The disadvantage of the emissive display is the high power consumption that results from the low emission efficiencies.

Cathode ray tubes (CRT) are currently the dominant electronic displays, except for pure alphanumerics. They are the standard of performance to which all other displays are compared. The CRT is a vacuum tube with a cathode luminescent phosphor that is bombarded by a position-controlled electron beam. Operation is generally either video raster-scan or random access.

In the raster-scan mode, the beam traverses the whole area of the display, line-by-line. Display brightness is determined by the beam power, phosphor efficiency, and duty cycle. The random-access mode is used with computer-generated nonvideo signals, typically alphanumeric or graphic information, which is usually generated with a stroke writing technique.

The CRT is not good for general aircraft because of the large ratio of tube-depth to viewing-face-diameter, the high voltages required for adequate brightness, the associated electronic circuitry, and the bulk and power requirements.

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The basic advantage of the CRT is the high peak brightness of greater than three million cd/m^2, which permits a high average brightness at TV display rates. The primary concern for television is the low duty cycle of typically 1/500 or 1/1000. In spite of this low duty cycle, there are displays with luminance levels of 10,200 cd/m^2 with resolution in excess of 40 lines/mm. The CRT can achieve these luminance levels due to a very high instantaneous luminance and a decay time that is long relative to the frame rate.

Another display requirement that is fulfilled by the CRT is the uniformity of both the threshold voltage and output beyond the threshold. Without uniformity there is an undesirable mottling of the picture. The CRT meets the uniformity requirement as there are more than 1000 phosphor particles within the electronic scanning beam; this averaging gives good uniformity of luminance across the face of the display. The redundancy of the display, i.e., multiple elements within the scanning beam, also gives a high degree of reliability. For a material to be considered for a display it must not only have the capability of high peak brightness but also must have intrinsic memory or persistence. The CRT meets both these requirements.

One of the CRT's major advantages is cost, which is 23 cents per character (Table 4-2). Further development is being funded and is inherently low in technical risk.

Table 4-2. Display Subsystem Projected Prices[*]

Number of Characters	Gas Plasma, $	Gas Discharge, $	CRT, $	Liquid Crystal, $	LED's $
32	6.05	5.29	3.56		
256	3.75	1.09	1.10		
512	2.33	0.78	0.66	0.40	0.75
1024	1.69	0.62	0.35		
2048	0.97	0.56	0.23		

[*]Original equipment manufacturer price per character including decode drive and refresh buffer.

A typical aircraft CRT display for an imaging forward-looking infrared sensor has a mean luminance of 171 cd/m^2, with a peak luminance of 680 cd/m^2, and requires 75 watts of power. The display is 11 x 8 cm and has an 800 line-per-picture height resolution. Envelope dimensions are 19x17x28 cm. Typical mean luminance levels for alphanumeric CRT displays will run as high as 1710 cd/m^2. The cost of a commercial TV display is $100 and a MIL spec unit will cost between $4000 and $5000.

The size of a CRT suggests using flat panel displays. Unfortunately, existing flat panel materials are not bright enough without increased persistance (inherent memory) or creating persistence by use of electronic on-site memory. Consequently, the problems and requirements of matrix-addressed displays with intrinsic or on-site memory must be considered.

Matrix-Addressed Displays -- Today, the potential for flat-panel video technology is limited to liquid crystal, gas-discharge, and possibly electrophoretic devices. Little effort has been devoted to the problem of addressing or signal distribution in multi-element displays as compared to the development of novel display materials. Therefore, the major current problem is getting the display message to all points on the screen; the display material itself becoming a secondary problem.

It is necessary to distinguish between active and passive matrix addressing. Active matrix addressing is defined as containing gain-producing, switching, and/or memory elements at every display cell. A passive matrix, in contrast, is normally composed of two sets of parallel conductors oriented at right angles to each other, with the display medium sandwiched in between. The major problems associated with passive matrix driven displays are: 1) the excessive demands placed on the electrical and optical characteristics of the display material, and 2) the complexity and cost of the external drive electronics. All of these problems can be solved or bypassed by the development of active matrices.

The function of the active matrix is to integrate the electronic functions and to compensate for the deficiencies in the electro-optical characteristics of the chosen display material. Liquid crystal displays, for example, have slow response times and electroluminescent displays require comparatively high voltages and lack inherent memory. Field-effect liquid crystal panels, with their own capacitance and high impedance, form their own memory. Consequently only a transistor is required at each display element to gate the initial charge (Figure 4-13). Electroluminescent displays, on the other hand, of either a-c or d-c, require a more complex circuitry due to high voltages and significant current levels. (Compare the circuits in Figures 4-13 and 4-14.)

Most flat panel display schemes use a matrix arrangement in which the individual display elements are connected between row and column electrodes. All elements along a row and column are partially stimulated when a single element is addressed at the *intersection of a row and a column* because all elements of the matrix are permanently interconnected. Therefore, most elements will be partially excited (cross talk) many more times than directly excited. Each element must have a sharp threshold above the partially excited level to have adequate contrast. An additional diode is required in display media not having this inherent sharp threshold.

Matrix-address arrays are generally operated a line at a time such that each element in the line can be driven for a full line time rather than for just one element time. This increases excitation time by a factor of the number of elements in a horizontal line, increasing the output brightness of the display as much as 500 times.

The longer excitation time relieves the drive electronics of handling short, high-powered pulses to a high-capacitance electrode. However, line-at-a-time operation at TV rates requires a 15-kHz shift register for the horizontal rows, a video sampler-distributor, two storage registers and a column
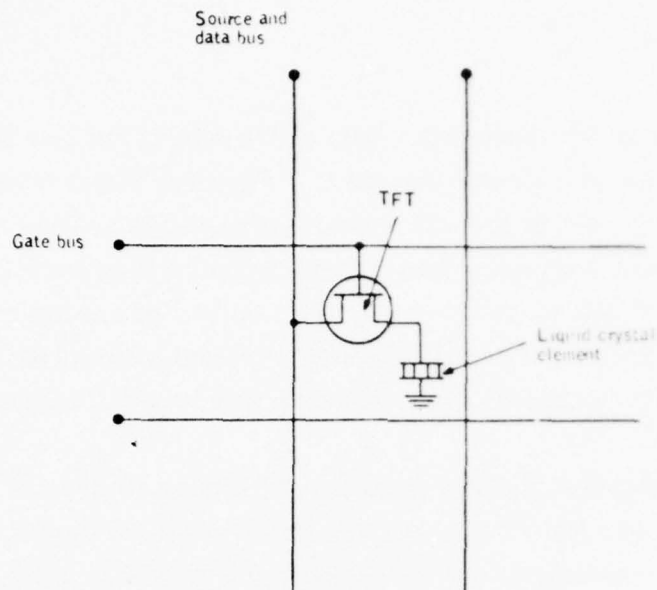
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Figure 4-13. Design of Elemental Matrix Circuit
for the Large-Area Liquid Crystal
Display
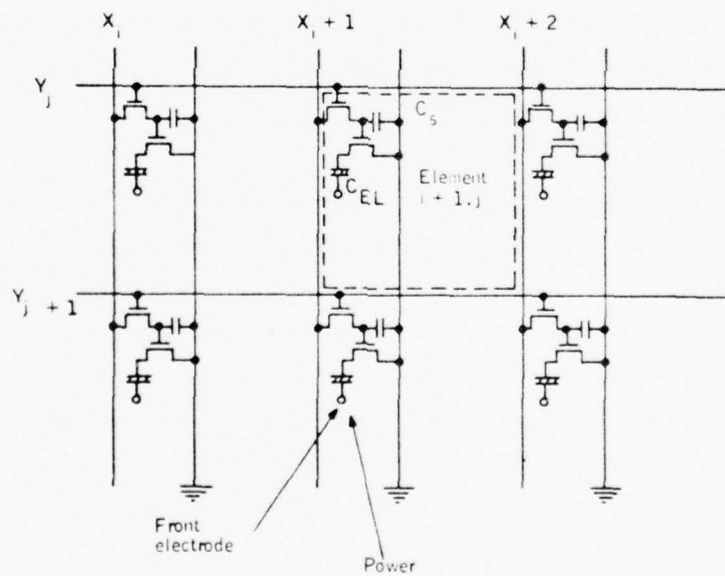
Figure 4-14. Design of Elemental Matrix Circuit
for the 6 by 6 Inch, 20 Lines/Inch
EL Display

driver (see Figures 4-15 and 4-16). The video signal for one line of information is fed into the sampler-distributor. Parallel video information is then stored in one register while the other storage register is feeding the column drivers. The storage registers and column drivers may be either analog or digital, but it is difficult to produce a large number of analog circuits with the same characteristics thereby avoiding vertical streaks in the picture. Thus, digital circuits are preferred to overcome this difficulty.

The average brightness of matrix displays developed to date is not as great as desired. Table 4-3 lists the expected maximum brightness for various display media when operated in a line-at-a-time format. This problem can be eliminated by incorporating an analog memory driver at each picture element location (Figure 4-16), which would maintain the display element excitation during the whole frame time and increase display brightness accordingly. Moreover, the memory elements must either control an external power source or act as amplifiers, which creates problems of element-to-element uniformity.

The need to avoid an unmanageably large number of connections and to provide integrated electronic circuitry leads to the large-scale-integration (LSI) concept of the entire display. Monolithic integrated circuits of matrices over two to three inches may be beyond the present or near-future capability of silicon technologies (Ref. 12). However, thin-film technology appears adequate for large-area active matrices and can be integrated with a large variety of display media. Thin-film transistor work is currently being conducted by Westinghouse and Aerojet General to build large active matrices.

It is not clear which technology thin-film transistors (TFTs) or silicon processes, will eventually produce usable matrix displays. A one-inch square silicon matrix is huge by silicon integrated circuits (IC) standards; shorting problems, insulator pin holes, metalization, wafer breakage,

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Figure 4-15. Block Diagram of Matrix TV Display
(Diode shown can be inherent feature
of display elements ($V_S \geq V_O$)

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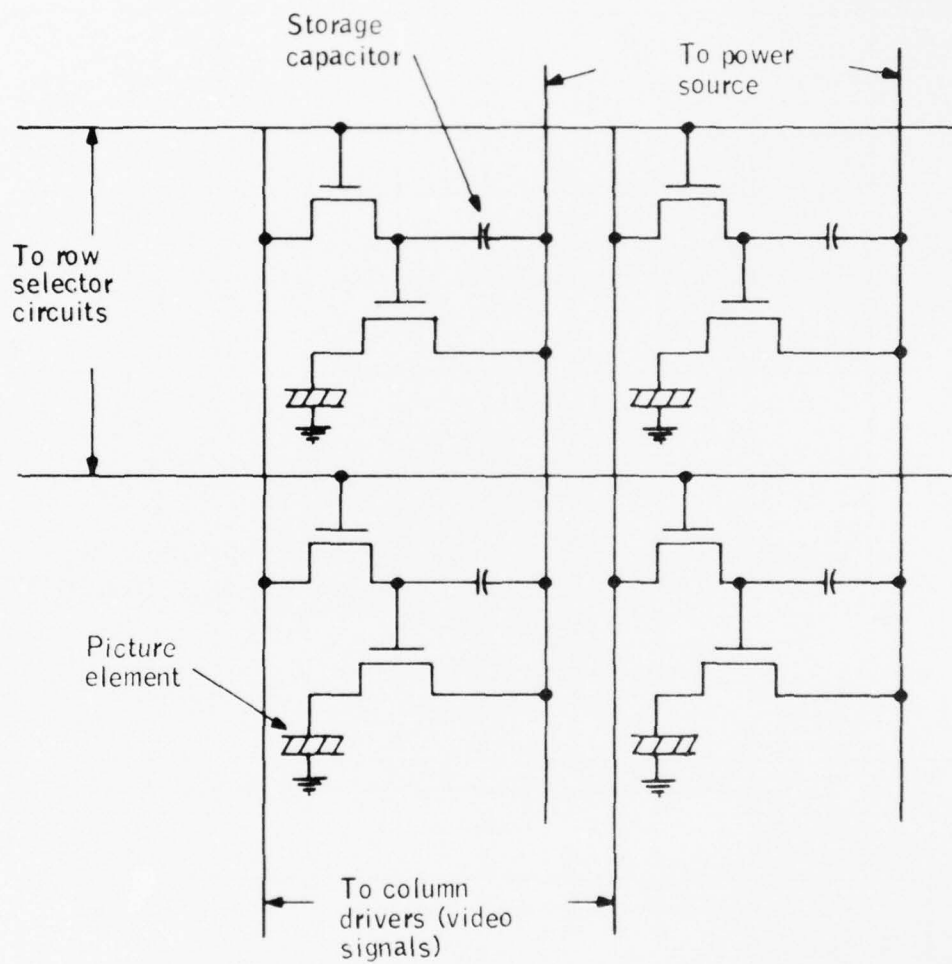
Figure 4-16. Circuit Configuration Needed for Frame Storage in Matrix Display

Table 4-3. Average Brightness and Luminous
Efficiency of Display Media

Display Type	Peak Brightness (Cd/m^2)	Maximum Average Brightness at 1/5000 Duty Factor (Cd/m^2)	Efficiency (lm/w)
Plasma	7500	10-15	0.5-1
AC Electroluminescent	500	1-5	5-10
DC Electroluminescent	3000-5000	25-50	0.5-1
Light Emitting Diodes	5000	5-10	0.5
Catholuminescent phosphors	$\gtrsim 100,000$	$\gtrsim 500$	100

in-process inspection and testing are the problems encountered with obtaining
the needed crystalline perfection over large areas.

The key problem in thin-film technology is the need for a 100 percent area
yield in all process steps. This is different than the semiconductor circuit
manufacture where many chips are formed simultaneously on a single wafer
and 100-percent wafer yields are neither needed nor expected. The thin-film
deposition sequence is long, somewhat complex, and subject to operator
errors. Not only mask fabrication (for thin-film deposition) but also the
alignment during the deposition steps must be perfect. However, mask loca-
tion changing, deposition material sequencing, and thickness monitoring can
all be done by automatic equipment. Also, the process steps are quite fast,
therefore, a large output-per-machine can be expected with reasonable yields
as manual operations are eliminated.

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<u>Passive Display Material Types</u> -- Liquid crystal, electrochromic, electro-
phoretic, and PLZT are four examples of low-power passive displays. These
displays do not emit visible radiation; rather they control the passage of
externally generated light through the display. Structurally, these four
displays have similar principal operations but dissimilar properties.

<u>Liquid Crystal Displays (LCDs)</u> -- Liquid crystal materials have the
normal solid and isotropic liquid phases of normal liquids, but they also have
a third phase which occurs between the solid and the isotropic liquid phase.
In this intermediate phase, the liquid crystal flows like a fluid but exhibits a
crystalline organic state. The molecules are usually long and rod-like, and
are responsible for the display-related anisotropic properties.

The liquid crystal is confined between two glass plates with their conductive
coatings in contact with the material. The electro-optic phenomena can be
divided into two groups: 1) those caused by dielectric forces and the so-
called field effects; and 2) those induced by a combination of dielectric and
conductive forces.

The most promising material and arrangement results in a cell structure
called the twisted nematic. Linear polarized light propagating perpendicular
to the cell is rotated approximately 90 degrees. Maximum light transmission
is obtained by orienting a crossed polarizer and analyzer. The transmitted
light decreases when the applied voltage exceeds a certain threshold voltage
and the liquid crystal molecules start to change their orientation and the
polarization of the display.

The advantages of LCDs are a low voltage and low current, which allow the
cell to be driven by CMOS ICs and the fact that their contrast is independent
of ambient light levels. The disadvantages are a slow response time (10 to
100 msec), and the difficulty of multiplexing. They have a limited operating
temperature range, and the viewing angle affects the contrast.

Electrochromic Displays (ECDs) -- An electrochromic material is one in which the color is changed by an electric-field current. One version uses an aqueous solution of a special organic dye contained between a pair of transparent electrodes. This display relies upon the oxidation-reduction reaction of the dye controlled by the application of voltage to the electrodes. The dye is colorless in the oxidized state. Application of about two volts across the electrodes reduces reactions, resulting a dramatic change in color. When the polarity of the voltage is reversed, the color compound oxidizes back to the colorless state. Another type of ECD uses a solid, inorganic film as the electrochromic material. A glass substrate with a transparent conducting layer or electrode is coated with a thin film of the material. A layer of insulating material is deposited over the film, followed by a second electrode. The film is colorless in the normal state, but when a voltage is applied the display appears blue. When the polarity is reversed, the film again becomes colorless.

The advantages of electrochromic material are that it operates on five volts or less, and its appearance does not change with the viewing angle. Its disadvantages are a slow response time (between 20 to 200 msec) and difficulty in multiplexing.

Electrophoretic Displays -- This type of display uses pigment particles of one color suspended in a liquid of a different color. The suspension is sandwiched between a pair of electrodes, at least one of which is transparent. The pigment particles are held in a colloidal suspension and carry a charge. When the electrodes are charged, the pigment particles move toward the front electrode, where they collect to scatter the ambient light, making the display change color. Reversing the polarity causes the particles to move towards the outer electrode, changing the color of the display to that of the suspension fluid.

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These displays operate at low voltages (less than 10 volts) and are legible over a wide range of viewing angles. On the other hand, they have a very long response time (in 100's of msec) and the particles may eventually settle out of suspension or may be damaged by shock and vibration.

PLZT Displays -- PLZT is a transparent, ceramic, electro-optical material with voltage-dependent transmission properties. Because the material is in the solid state, it is necessary to use the optical properties of induced birefringence and of scattering. The birefringent mode is implemented by operating the material such that the applied voltage will vary the polarization of the transmitted light. The effect can be observed through an analyzer sheet as a change in intensity. In the scattering mode, the transmitted light is diverted from the normal propagation direction and scattered into a larger solid angle by the application of the voltage to the material. Within these two modes of operation, the material can further be classified according to its memory. The material may either have memory or none in either mode of operation.

A significant advantage of the material is its potential for intrinsic memory, which would permit displays with high contrast. However, its disadvantages of a high drive voltage (40 volts), cracking under stress, poor contrast, and small viewing angles are also significant. The requirement for transverse excitation requires either depositing interdigitized electrodes, or cross-slotting the material itself. Both techniques are difficult for matrix-cell fabrication.

Emissive Displays Material Types -- Three examples of emissive displays are light emitting diode (LED), gas plasma devices (GPD), and electro-luminescent devices (ELD). These devices emit visible radiation and, consequently require more power than the passive display.

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Light Emitting Diode -- This device is essentially an electro-optical transistor. Basic components are the diode leads, crystal chip, and possibly a diffuser lens. Diode-chip-emitted light is proportional to the current flow. Luminous levels up to 340-1400 Cd/m^2 are common without heat sinking and cooling. Voltage levels vary from 1.4 to 4.5 volts, depending upon the material. Color of the device's output is primarily red, but green and yellow are available and a blue output is under development. LEDs are high-current, low-voltage devices that are compatible with discrete MOS transistors.

The advantages of LEDs are that they can be molded into a large variety of shapes with a large range of optics. They are compatible with the low-voltage supply provided by conventional transistor circuits. They are rugged, have a high reliability with a long life, and are resistant to temperature change. The disadvantages are that the material is relatively expensive and the LED is not readily driven to maximum brilliance by MOS ICs, particularly CMOS ICs, due to the electrical current requirements. Consequently, they are not likely to be used in large-matrix-driven displays.

Gas-Plasma Devices (GPD) -- A plasma panel is a gas-filled device. It is the most advanced class of all flat-panel displays. It has two modes of operation: ac and dc. The gas fill is usually neon or a mixture of noble gases with other inert gases, such as nitrogen. A panel-resolution element is defined by a very small gas volume between orthogonally oriented sets of parallel conductors, one on the front transparent surface, and the other on the back transparent surface. The visible plasma discharge appears when a high-voltage, low-current charge is applied between the electrodes. Some of the many display types are self scanning and require few electrical connections. These displays have been under very intensive study to develop real-time TV displays as they are closest to having all the required characteristics.

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The advantages of d-c GPDs are that they have sharp thresholds with a high
contrast ratio. They also permit the use of a gray scale. The response
time is fast enough for line-at-a-time addressing. The disadvantages are that
they primarily come in the color red, require 170 volts, and have no inherent
memory.

Electroluminescent Displays (ELD) -- These devices are essentially an
electrical, luminous capacitor consisting of two flat electrodes, one of which
is transparent, enclosing a space filled with an electroluminescent phosphor.
When a low-current, high voltage is applied to the electrodes, a field is
created causing the coated areas to emit light. Most displays are single
colored, usually green or orange because of the higher efficiencies. The
potential may be ac or dc, depending upon the structure, but they usually
are ac.

The advantages of these devices are that they can be driven by TFTs for large-
scale matrix displays. They are lightweight, have low current requirements,
and produce no heat. They have a high reliability and a long life and are not
affected by temperature, vibration, or shock. Luminance levels are usually
only 15 to 100 Cd/m^2, and they come in only one color for a particular dis-
play type, but that may be red, green, yellow, blue, or white. The disadvan-
tage is the high voltage requirement (up to 600 volts).

Display Material Comparison -- The basic parameters for comparing candi-
date display materials are: visibility in the high ambient illumination of the
cockpit, luminance, contrast, life, power requirements, and resolution.
Size and bulk are not compared as the materials are all intended for flat panel
displays, and it is assumed that panel depth will not be a problem as drive
electronics and probably be miniaturized. If the bulk of the electronics
becomes a problem for high-voltage displays, they can be mounted in a
remote location. The panels are expected to be less than one inch thick.

Table 4-4 presents display material characteristics, and a detailed discussion of these parameters is presented in Appendices I through P of Ref. 7. The pacing requirements for a display material are contrast and luminance. A specific case for these requirements is presented in Table 4-5. A discussion of these requirements and the deviation from them is presented in the attached Appendix A. Because data on reflectance is not available in the literature, five percent reflectance is assumed for all materials. A display or time-averaged contrast of 10:1 is also assumed as a requirement. The intrinsic material contrast and luminance is equal to the time-averaged contrast and luminance only when the display elements are on continuously (nonmultiplex or memory matrix addressed). However, the contrast luminance is reduced when a character is multiplexed or a matrix is addressed one line at a time without memory.

It should be noted that passive display luminance is a function of reflected ambient illumination. It is assumed that the cover glass reflectance is lower than the display reflectance and, therefore, display contrast remains constant with illumination.

Table 4-5 presents the contrast and luminance requirements for three conditions of high ambient illumination in the aircraft cockpit. The first condition is when the display is shielded from all ambient illumination, and the required display luminance is established by eye adaption to bright white clouds. The second condition is when the display is shielded from direct sunlight, but is illuminated by reflected light from white clouds through the cockpit windows. The last condition of direct sun illumination is the most difficult for active display visibility. This table does not include the use of ambient light suppression techniques for active displays because specific display reflectance data is not available. Therefore, Table 4-5 presents a worst-case set of requirements and provides a basis for a relative comparison of display materials.

Table 4-4. Display Material Characteristics

Material and type of display	Intrinsic contrast ratios	Present resolution, line/cm	Ultimate resolution, limit, lines/cm	Response times	Voltage and current	Compatible electronics	Temperature range, °C
LCD (Passive)	15:1 to 50:1 possible	40	100	10-20 msec rise time; and 100-300 msec decay time	5V $1~\mu W/cm^2$	CMOS IC	0 to +70
PLZT (Passive)	100:1 at 90 V	Not reported	Not determined	1 to 100 μsec	30 to 50 V μA	Discrete transistor	Not determined
LED (Emissive)	50:1	20	40	100 nsec	1.4 to 4.5 V $1.5~A/cm^2$	Bipolar transistors to interface with MOS drivers	Wide
GPD (Emissive)	50:1 (time averaged)	20	40	1 to 10 μsec	170 V $0.16~A/cm^2$	MOS to swing lower voltage of ±25 V on 135 V bias	Wide
EPID (Passive)	20:1 to 40:1	Unknown	Unknown	50 to 100 msec rise time and 100 msec decay time at 50 V	10 V to 30 V Low current	Discrete transistors or PMOS IC's	-15 to +50
ELD (Emissive)	>50:1 (Time averaged)	8	40		200 to 600 V (5 kHz ac) $0.03~A/cm^2$	TFT matrix and high voltage FET's	Wide
ECD (Passive)	Limited contrast	Unknown	Unknown	100 to 500 msec	< 5 V High current	Bipolar transistor more suitable than MOS	-20 to +70

Table 4-4. Display Material Characteristics (Concluded)

Viewing angle and contrast sensitivity	Life and reliability	Color and luminance, cd/m^2	Intrinsic memory	On-site memory	Comments
15° to 20° *Angle sensitive*	50,000 hr	Not applicable	No	TFT and silicon chips	• Matrix displays under development • Require heaters for temperature control • Ample development funds available from computer and watch industry for multiplex displays
Poor contrast beyond 15°	Life not determined Not rugged	Not applicable	Yes	TFT or ferroceramic	• No high-volume user • Seven-segment numerical display available in birefringent mode
Lenses to increase luminance *decrease view* angle	10^6 hr High reliability and rugged	Red, green, yellow, orange 1000 peak	No	Silicon transistor	• Limited to small displays • Power limits display brightness • Red is poor color for aircraft displays
Wide	> 20,000 hr Rugged and reliable	Red, orange, blue, green 150 (time averaged)	Potential for memory	Yes	• Most advanced flat panel technology • Supported by TV industry • Sharp threshold for good contrast and gray scale being developed
Very wide Not sensitive	10^5 to 10^7 cycles in 3000 hr	Not applicable Not reliable	Yes	TFT	• No application yet
Very wide Not sensitive	20,000 hrs Rugged	Red, green, yellow, blue, white 140 to 340 (time averaged)	Phosphor decay	TFT	• Thin, lightweight, flexible • Matrix display under development
Very wide Not sensitive	10^{+6} to 10^{+7} cycles Unknown	Blue, green Not applicable	Yes with open circuit voltage	Unknown	• Matrix development unlikely • New technology

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Table 4-5. Flat Panel Display Material Intrinsic
Contrast and Luminance Requirements

	Reflective passive displays (a)				Active displays (a)							
	Nonmultiplex or onsite memory matrix address	Multiplex or nonmemory matrix address, 30 frames/sec			Nonmultiplex or onsite memory matrix address		Multiplex or nonmemory matrix address, 30 frames/sec					
		16 line	100 line	500 line			16 line		100 line		500 line	
	Contrast	Contrast	Contrast	Contrast	Luminance, cd m^{-2}	Contrast	Luminance cd m^{-2}	Contrast	Luminance, cd m^{-2}	Contrast	Luminance, cd m^{-2}	Contrast
Luminance and contrast	C	$\frac{C1}{N}$	$\frac{C1}{N}$	$\frac{C1}{N}$	B1	C	$\frac{B1}{N}$	$\frac{C1}{N}$	$\frac{B1}{N}$	$\frac{C1}{N}$	$\frac{B1}{N}$	$\frac{C1}{N}$
White cloud eye adapted display shaded from ambient illumination	10:1	53:1	340:1	1700:1	680 to 1700 Peak	10:1	3200 to 9100	53:1	2×10^4 to 5.7×10^4	340:1	10^5 to 2.8×10^5	1700:1
Luminance and contrast	C	$\frac{C1}{N}$	$\frac{C1}{N}$	$\frac{C1}{N}$	$RL(1-C)/(\frac{C}{C_R}-1)$	>10C	$RL\frac{1}{1}/(\frac{C}{C_R}-\frac{1}{1})$	>10$\frac{C1}{N}$	$RL(\frac{1}{1}-C)/(\frac{C}{C_R}-\frac{1}{1})$	>10$\frac{C1}{N}$	$RL(\frac{1}{1}-C)/(\frac{C}{C_R}-\frac{1}{1})$	>10$\frac{C1}{N}$
Ambient sky illumination of display	10:1	53:1	340:1	1700:1	4 460	100:1	2.6×10^4	530:1	1.6×10^5	3400:1	6.2×10^5	17 000:1
Direct sun illumination of display	10:1	53:1	340:1	1700:1	16,000	100:1	9.2×10^4	530:1	6×10^5	3400:1	3×10^6	17 000:1

(a) Contrast ratios and luminance are peak or intrinsic required levels for display material

Symbol	Definition
C	Desired time-averaged contrast ratio, 10:1
C_R	Material intrinsic contrast
L	Number of lines or characters to be sequentially addressed or multiplexed during refresh period
N	Number of refresh periods in eye integration time of 0.1 sec, 3
B	Desired time-averaged luminance of display
R	Display material reflectivity

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Table 4-5 shows that all passive display materials have adequate intrinsic contrast (10:1) for nonmultiplex or memory matrix address displays. All display materials except electrochromic (ECD) and perhaps electrophoretic (EPID) have enough intrinsic contrast (53:1) for use as 16-character line-multiplexed or nonmemory (line-at-a-time address) matrix display. However, there are no materials that have adequate intrinsic contrast when a high resolution (100 to 500 characters/line) nonmemory display is required. PLZT may have a future potential of 1000:1 contrast, but it requires a high drive voltage. On-site memory is a better approach to the development of high-resolution passive displays as any material with lower intrinsic contrast but superior electrical characteristics can be used.

Intrinsic contrast requirements for active displays become much higher than for passive displays when the active display is in ambient illumination (Appendix A). These ratios range from 530:1 to 17,000:1, and none of the materials meet these requirements. On-site nonlinear devices could be used to improve the material excitation threshold (Appendix A) and contrast; however, on-site memory can be provided as easily and then high contrast would no longer be required. It should be noted that intrinsic luminance requirements for active displays in ambient illumination (Table 4-5) becomes much larger than the capabilities of the display materials. Even two orders of magnitude reduction in luminance requirements (Table 4-5) for high resolution displays through the use of ambient light suppression techniques will not help. Consequently, an on-site memory is definitely required for both passive and active high-resolution matrix displays.

Passive Display Status -- The most promising passive display material is liquid crystal with an on-site memory (see Appendix I of Ref. 7), which is being developed by both Hughes Aircraft and Westinghouse. Currently, there appears to be enough development funding for military applications.

The next most promising class of passive display materials are the electrophoretics (EPIDs), with the colloidal-sized TlO_2 particles (Appendix K of Ref. 7) as the best candidate. As there does not appear to be a specific aircraft-oriented program on this material, there is more risk than in the case of LCD development.

Active Display Status -- CRTs are currently the best device for aircraft displays and will be used in the various tradeoffs, analyses and examples in their report. However, there is a high probability that GPDs with a performance suitable for aircraft displays will be available in the 1980's. Because of the current effort being expended on GPDs for TV use, the risks involved are the suitability of the physical configuration (size mostly) and the question of how much ambient light suppression and shielding will be required.

LEDs will be available in large volume and many types, but because of the relatively high drive currents required for high brilliance, there are some doubts as to the development of the on-site memory necessary for high-resolution matrix displays. There is no doubt as to the availability of suitable alphanumeric displays.

Long-Persistence Phosphor CRTs -- Long-persistence P-7 and P-14 phosphors have been used for many years to display the radar and IR line-scan imagery. The disadvantages of using long persistence tubes are a low brightness level, fixed and nonlinear persistence, and an inability to selectively erase.

The low brightness of this type of tube makes it impossible to use such a display in aircraft cockpits without a visor or hood to shield ambient light. Even then, the operator is forced to adjust quickly from exterior ambient light levels as high as 10,000 foot lamberts to the low brightness of CRT long persistence phosphor. This display can be used where ambient light can be controlled and the long persistence CRT provides an acceptable display for low scan rate sensors.

Even under these conditions, the image smears, if the image from one frame is not completely erased by the time the new image is painted on the display. However, adjustments to the display to promote a rapid fading will also cause an annoying fade rate which degrades the operator's recognition performance. Therefore, other displays were developed, such as the direct-view storage tubes (DVST).

Direct-View Storage Tubes (DVST) -- A direct-view storage tube display provides a bright, nonflickering image with a controlled persistence. The high brightness is a result of a constant source of electrons to illuminate the viewing screen phosphor during the viewing operation. The flooding electron beam is modulated by the stored charge pattern on dielectric mesh located immediately in back of the phosphor. The picture observed on the face (phosphor) of the tube is a projection of the charge pattern on the dielectric mesh. This charge pattern is written on the dielectric by the action of a focused electron beam. Both conventional and fast-erase storage tubes are available. A conventional DVST requires several tenths of a second for erasure, and is too slow for high-frame-rate FLIR or LLLTV sensors. The fast-erase storage tube can be erased in one to two milliseconds, and therefore presents a bright TV display.

However, fast-erase on a DVST loses resolution, gray scale and scan-to-scan interference. Also, symbology presented on either a fast-erase or a conventional DVST smears when it is moved across a stored image.

Typical characteristics of a fast-erase DVST are 100 stored lines per inch of resolution (shrinking raster), 10 percent MPF at 68 cycles/inch, 800-foot lamberts of brightness, 100-K inch/second writing speed, a storage time of 10 seconds, and 6 shades of gray.

Fast erase DVST appears most applicable where the radar ground mapping is of a poor quality; nonstored symbology is not required simultaneously with a stored image; image fade, smear and gray scale is not important (target recognition is not required) and TV image brightness is more important than resolution or gray scale. Fast erase DVSTs are not suitable for presenting E-O sensor imagery for a high quality multifunction display. However, a conventional DVST can display radar information for combining with E-O imagery from another, more suitable display.

Short Persistence Standard CRTs -- The conventional short persistence CRT is the best choice if a single indicator is to be used for a multifunction display monitor. However, this implies the requirement for some sort of scan conversion of the slow scan radar sensor's video. The short persistence CRT has a high resolution and high brightness. It also has good visibility under high ambient light conditions when a narrowband phosphor and a matched notch filter is used.

It is assumed that the standard TV raster video scan rates is the best approach for the aircraft display. However annotation of display with alpha-numerics requires a selection of the type of deflection system. There appear to be three options: a wideband deflection system; a dual mode deflection system; or an all-raster energy recovery deflection system.

The first option is the wideband deflection system, which is capable of medium-speed caligraphic generation of synthetic symbology during pure symbol modes and also raster scanning when an EO sensor imagery is selected. When a raster sensor is displayed, overlay symbols are generated during the raster vertical retrace. The advantage of writing a symbol during the vertical retrace period is that the brightness of the symbol adds to the brightness of the image. Therefore, the symbol can be seen even when superimposed on a peak-white area of the image. In other words, it becomes whiter than white. This ensures that the synthetic data is seen everywhere with good contrast

for the image picture. The disadvantages of the wideband deflection amplifier are the excessive power requirements and heat dissipation. Another disadvantage is the complexity of the wideband deflection system created by the relatively high writing speeds associated with the sequential construction of stroke-written symbols within the available flyback time. The limiting factor is the quantity of written symbology required during the one millisecond of vertical retrace time.

The dual-mode deflection system is capable of either sequential caligraphic beam steering as for the wideband deflection system in purely symbolic modes, or a more efficient scanning technique which minimizes power dissipation during the TV raster scanning mode. This design could also include a limited raster symbol overlay using video mixing techniques during the TV raster mode. All system performance requirements are reduced, since the stroke writing applies only to the symbolic mode over which some 17 milliseconds (60 field rate) are available and this results in a reduced writing speed and simpler waveform generation. However, additional complexity is needed to generate the limited number of raster symbols which are in the TV raster scan mode.

The last option is the all-raster energy recovery deflection or tuned system. This approach generates all the synthetic symbology in the raster and mixes it with the E/O video when imaging sensors are selected. By comparison, this technique is the least complex since there is no writing speed limitation on symbol generation. The TV raster approach is the most cost-effective from the overall system point of view, a fact proven by its choice for use in commercial television receivers. The key advantages are: 1) simple, low-cost, low-power, highly reliable and easily maintainable CRT indicator design; 2) simple "in-raster" symbol generation; 3) direct compatibility with many electro-optical sensors; 4) a simple interface for repeater displays; 5) compatibility with standard TV video tape recording and playback equipment for rapid mission evaluation and training; and 6) compatibility with TV video data

links for real-time transmission of radar video for evaluation and analysis at remote sites equipped for TV reception and displays. The disadvantage of the "in-raster" symbol writing is that, in some areas, the symbol becomes indistinguishable unless techniques such as black bordering of the symbol is used. However, in this case, the black border obliterates some of the image. Even so, raster symbol generation is generally more effective for display with a large quantity of characters, while the cursive approach has an advantage for displays of symbols having a large quantity of vectors or circles. The raster approach also has a greater potential for inverting character contrast, generating electronic windows, drawing broad lines, and generating other area symbols.

Imaging Combining Techniques

Rear-Port CRTs -- Image combining with a rear-port CRT has already been discussed for moving map and CRT imagery. This device has a flat optical window near the gun, which permits projecting an optical image on the back surface of the phosphor.

The brightness of a rear-port CRT is limited by the projection optics. Limited space within a display package not only confines the heat for high power (high brightness lamps) operation, also tends to burn the film. Good visibility of the fine detail on conventional maps and charts is difficult under high ambient illumination conditions. Therefore, a map image is generally limited to low brightnesses of between 100 and 200 foot-lamberts, and must be viewed with a hood in direct, bright sunlight.

Another problem with optical projection systems is the hot spot in the center of the screen. This is generally avoided by roughening the glass on the inside of the CRT to diffuse the image.

Brightness of rear-port CRT phosphors can exceed 200 foot-lamberts, but superimposed map imagery would then not be visible. Larger display packages may permit brighter map images, but phosphor brightness is reduced (one half) by the lack of an aluminized screen behind the phosphor (light from the projection optics cannot penetrate the aluminum film).

Applying a rear port to a DVST is not feasible since the storage mesh is opaque. This suggests, in addition, investigating an optically transparent storage mesh. At the present time, rear-port CRTs are limited to low-ambient lighting conditions, use with a viewing hood.

Dual Phosphor CRTs -- There are at least two approaches that use dual re-
sistance phosphor CRTs for image combining. The first technique uses one
gun that excites both a blue, short-persistance phosphor, and an orange,
long-persistance phosphor. Blue and orange filters reduce the interference
from the unwanted phosphor persistance. The blue phosphor filter permits a
fast raster scan TV sensor image to be shown while the orange filter permits
viewing the slow-scan radar imagery. This combined approach penalizes
both modes due to the attenuation of the filters. Furthermore, the drive
electronics and display must function at two different scan rates. A second
approach excites the phosphors by electron beams with different acceleration
potentials. The lower acceleration beam excites the short persistence
phosphor alone for imagery at TV rates. The higher acceleration potential
excites both the long- and short-persistence phosphors for radar, slow-scan
imagery alone. This technique has the advantage of requiring no color filters.

The dual-persistance phosphor/filter CRT is most useful where no ambient
light falls on the display, and the operator has little time pressure and no
competing task. These disadvantages can only be justified where cost is an
overriding consideration, or where a radar operator is a part of the crew.
The dual acceleration-potential CRT has greater potential for brightness, and
therefore usefulness, since it does not use optical filters. However, all
approaches using long-persistance phosphors have all the disadvantages dis-
cussed earlier: low brightness; and either a rapid fade or smearing. Other
approaches would probably be preferred.

Multimode Tonotron (Hughes Aircraft Co.) -- The multimode Tonotron tube,
a special type of a DVST, is discussed as a separate image combining tech-
nique since it has a potential for sequentially presenting radar and TV imagery.
The Tonotron has five guns: a stored writing gun, a TV gun, a symbology gun,

an erase gun, and a flood gun. The stored wiring and flood guns permit projection of radar imagery with a high viewing brightness, good resolution, good contrast and a good gray scale. The TV gun permits using the standard short-persistence phosphor of the Tonotron for E-O imagery with good resolution and good gray scale, but with brightness too low for viewing under high ambient light conditions. Non-stored symbology is presented by the separate symbology gun, which permits symbology to be moved across the stored video image without smearing.

The erase gun allows selective erasure of a stored image. Through its use, smearing of slow-scan radar imagery is avoided by erasing the previous image sweep before writing in a new sweep. Consequently, the multimode Tonotron can present acceptable radar imagery for target recognition with non-smearing symbology. However, its high-quality TV imagery can only be viewed under low ambient light level conditions (or with a hood). Stored radar and TV imagery can be viewed simultaneously but not with non-stored symbols, unless the TV and symbol gun are time-shared. The limitation of the Tonotron in aircraft may be its sensitivity to stray magnetic fields and vibration.

Video Mixers -- Many systems are currently available for mixing TV-compatible video imagery. These systems routinely offer as many as 100 special effects pattern-generators. They include wipe patterns (inserting or transitions between video channels) such as bars, rotary, windshield, and many other combinations. Video inputs can be mixed or dissolved into each other with many types of edge and border effects.

Mixing is accomplished on an additive basis with faders controlling the brightness of each channel with an attenuation from 0 to 100 percent. Wipe patterns can be automatically programmed with transitions of from 10 to one-tenth of a second. Black, white, or drop shadow borders can be created around alpha-numerics. Spotlight effects can be created with circular, rectangular or diamond patterns at any ratio of brightness between the background and the scene within the spotlight. Joystick positioners are available

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to move single-wipe patterns anywhere within the display field. The aspect ratio of the special effect patterns can also be varied by a single control. Polarity can be inverted and blink rates varied.

The variety of special effects, ease of operation, and the preprogrammed automatic control of these video mixes is very extensive, and indicates a well-developed arsenal of circuitry and technique. Consequently, many forms of video inserting can easily be accomplished for aircraft application, with a minimum of technical risk. The major developmental task is to convert commercial units to militarized hardware.

Scan Conversion Tubes -- The problems with DVSTs and multimode Tonotrons (DVSTs) have led to a need for a device to store slow-frame-rate imagery separately. Such a device (a scan converter) can provide all the advantages of a DVST, as well as:

- Superior display using a CRT TV monitor

- Large selection of CRT sizes and shapes

- Potential application to flat-panel displays

- Nonsmearing symbology by "in raster" or stroke writing between frames

- Flexibility and growth potential to new sensors

- Multiple displays with one scan converter

Scan conversion tubes tend to fall into one of two main categories: the single-ended, and the double-ended. In the single-ended version the charge is deposited on and read from the same side of a storage mesh. A single-deflection system is used which is shared by the read and write beams. It follows that the reading and writing operation must be time-multiplexed, which means that, for many applications, two tubes are needed for a page-by-page mode.

The double-ended storage tube has separate read and write beam deflection systems on either side of the storage mesh. Charge is developed on one side of the mesh by the write beam and interrogated on the other side by the read beam. The charge pattern is written on the dielectric mesh by either a secondary emission or a bombardment-induced conductivity. The pattern on the dielectric modulates the scanning read beam on the output side. The read beam is scanned at the standard TV format of 60 fields per second, while the write input beam can be at any scan rate or format.

The advantage of the double-ended scan converter tube is that the write-in and read-out operations can be performed simultaneously. Its disadvantage is the extreme complexity of adjustment required during installation or replacement. Since the adjustments tend to vary, the periodic maintenance costs are also high. The end result is a system which is inadequately maintained, has a high replacement cost and low reliability, and has poor accuracy, dynamic range, and picture registration.

These problems can be avoided through the use of two single-ended scan conversion tubes. The procedure is to write one frame of radar imagery into one of the tubes. The next frame of radar imagery goes to the second tube. The TV monitor is switched between the tubes at the frame rate of the radar sensor. The image seen on the TV display is frozen over the radar frame period, approximately one second. The disadvantage of this approach is that the display is not updated continuously at the sweep rate of the radar (as with the double-ended tube). A further disadvantage is that the tube deflection circuitry must operate at both the slow-radar and fast-TV raster rates.

This approach has advantages:

- "Erase" before "write" is not required

- Close tolerance mechanical alignments for fine correction for deflection gain and offset are not required when replacing tube assemblies

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- Ease of packaging: the single-handed tubes are less than half as long as the double-handed tubes

- The tube and coil assembly need not be accurately aligned

- Unit operation does not depend upon the position of the two tube assemblies with respect to each other

- Lower cost

Digital Scan Conversion -- Storage tube scan converters can successfully meet specific needs of unsophisticated display systems. Until quite recently they have been cheaper, smaller, and consumed less power than digital scan converters of identical specifications. The main advantage of the storage tube is the virtual independence of its read and write scan patterns. However it is difficult to scan in random or discontinuous steps because of the self-inductance of the deflection coils. For this reason, display features which require variable read-out, frame overlap and image magnification tend to be performed easier with a digital system. Furthermore, rolling map presentations of moving platform radars are difficult to achieve with storage-tube converters. Also, the ten shades of gray of tonal quality of a stored picture is below that of commercial TV. The high impedance of the device lowers the signal-to-noise ratio, which degrades the overall picture quality. This degradation is compounded by areas of uneven leaks which produce patchy images. An optimal picture requires highly stable drive and deflection wave forms with careful setup and frequent readjustments. Filament life is anoth problem. Furthermore, the device is highly sensitive to extraneous magnet fields since the electrons in the read beam are repelled by the stored charge and the velocity of the electrons is momentarily reduced to zero. The environmental shortcomings of the storage tube seriously limit its use in a miliary vehicle.

These limitations have led to the development of digital scan conversion techniques. A digital-scan converter must be differentiated from a solid-state converter to avoid ambiguity. The solid-state converter is typified by the charge-coupled devices discussed in the next section. The digital-scan converter is also a solid-state device, but relies more on traditional digital logic design than the solid-state converter. All solid-state systems are reliable, easily maintained and require little or no readjustment in use. In addition, digital systems are easier to partition and simpler to integrate with existing computer systems. The main advantage of a digital system is its capability to produce a picture of definable quality within the constraints imposed by storage capacity, volume, and power consumption.

The digital-scan converter has additional capabilities:

- Picture hold
- Rolling update presentation
- Rolling map presentation
- Page-by-page presentation
- Variable line-by-line integration
- Field or frame update
- Polarity reversal
- Reservable line count
- Input magnification
- Image super-imposition
- Selective erase
- Controlled fade erase
- Multi-input
- Choice of TV raster rate
- Contrast bit suppression
- Reduction of resolution
- Histogram equalization
- Spatial filtering and gamma correction

- Clutter suppression and scan correlation
- Synthetic digital maps
- Level slicing
- Scale and geometry conversion

A digital scan converter samples the incoming analog video and converts it to digital codes corresponding to the number of amplitude levels (shades of gray) desired for each resolution element on the display. The digitized video is then stored in digital memory, which is read out at TV rates and converted to analog video for input to a TV display monitor (Figure 4-17). It is necessary that each storage cell be capable of encoding enough contrast levels to reproduce the image to the desired degree of fidelity. In practice, the maximum gray-scale resolution is limited by either the sensor, the display, or the visual acuity of the observer. Figure 4-18 (Ref. 13) shows the memory and bandwidth requirements as a function of resolution based upon a 4-bit (16 gray scales) digital code for each resolution element. The video bandwidth requirement assumes a 30-Hz TV frame rate with a 75 percent active display duty cycle.

Selective erasure of video information is automatically obtained with digital storage, since each resolution element is erased as new sensor data are stored. A digital scan converter provides high-quality imagery because: a) the digital memory is perfectly uniform; b) it can be designed to store as much sensor resolution as desired; c) it stores the full signal amplitude with as many shades of gray as desired; d) the image does not fade as a function of time or environment, and 3) the stored signals can be read out at a high signal/noise ratio.

It is expected that digital-scan conversion will find wider applications in new avionics systems, as the cost of digital memories and components continue to decline. Volume and cost of the converter is related to the computer memory market. Consequently, the volume of a digital-scan converter can be reduced to one-quarter and the cost reduced by a factor of five within the next five years (Ref. 14).
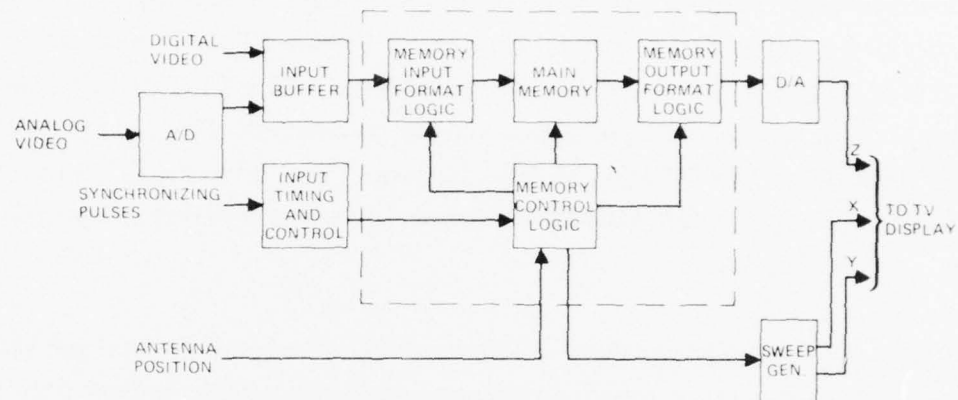
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Figure 4-17. Basic Digital Scan Converter Block Diagram
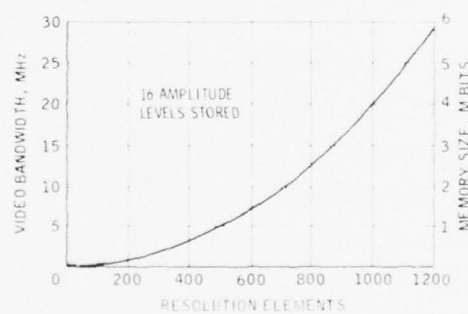

Figure 4-18. Digital Scan Con-
verter Memory
and Bandwidth

Solid-State Scan Conversion Using Charge Coupled Devices (CCD) -- There
are at least two techniques that use CCDs for image combining. The first
stores alternate fields to permit mixing of FLIR and LLLTV sensors at
different line rates; i.e., for this example 525 and 875 TV lines/frame. The
second approach uses a CCD-imaging sensor to convert slow-scan radar
imagery (on a DVST) to TV-compatible format. The advantages over digital
or doubled-ended tube scan conversions are cost and/or simplicity and
volume.

CCD Electronic Scan Conversion -- Current CCD technology will permit
frame storage of raster imagery to convert video from one frame rate to
another, for example from 525 TV lines/frame to 875 TV lines. It will also
permit a non-interlace to interlace format conversion, or vice versa. Two
CCDs must be used for alternate field or frame storage since "write in" and
"read out" are sequential operations for CCDs (Figure 4-19).

This approach implies a need for the simultaneous image presentation of
non-compatible raster FLIR and LLLTV sensors. If sequential presentation
were required, it would be simpler to use displays that can be switched to
alternate line rates. It is further assumed that a 525-TV line FLIR sensor
and a higher resolution 875-TV-line LLLTV sensor with equal FOVs are
being displayed on an 875-TV-line monitor. This requirement is realistic
since high-resolution LLLTV 875-TV-line sensors are common, while high-
resolution FLIRs are not.

The Fairchild CCD361 23,560-bit analog shift register is intended for analog
signal processing and temporary storage applications. It is organized in a
series-parallel-series configuration. Input voltage is sampled by a charge
injection port and generates proportional charge packets in a 190-element
serial-input register. The information is then transferred in parallel to
registers that transport the packets to a 190-element serial output register.
Clocking the output register then delivers the charge package to an on-chip
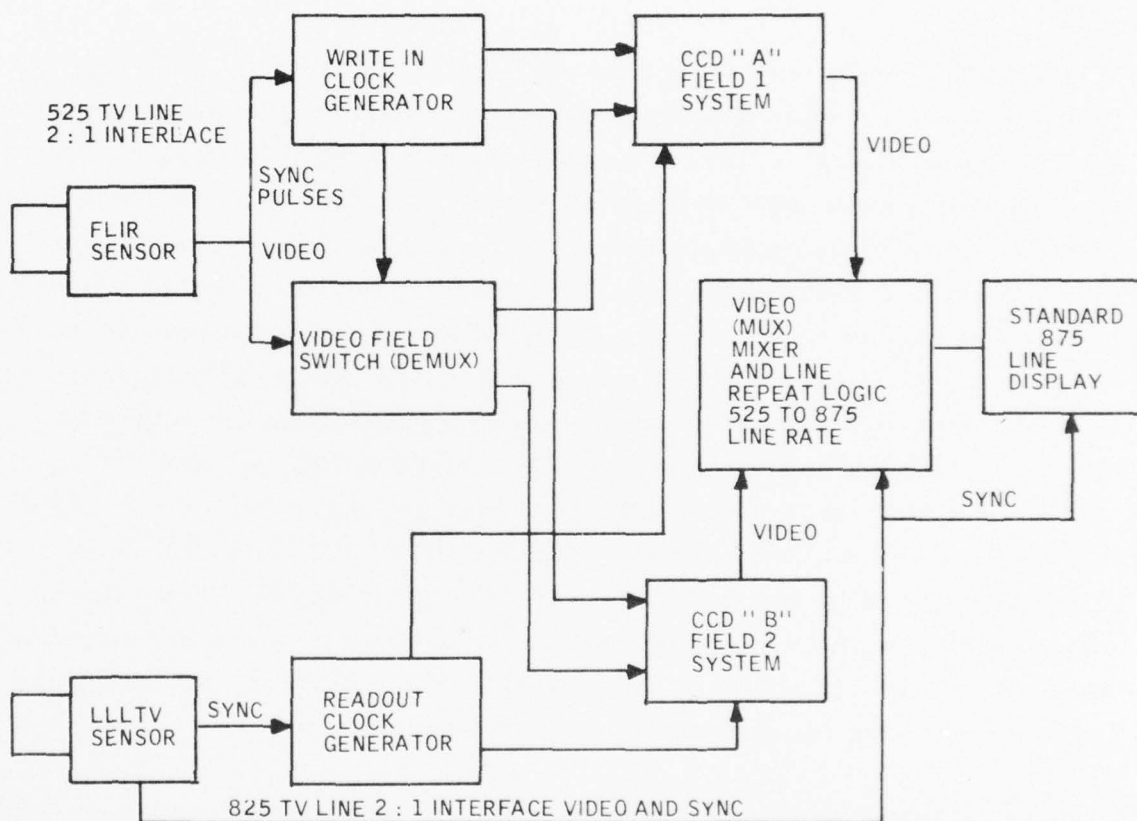
Figure 4-19. CCD Electronic Frame Scan Conversion System for Simultaneous Presentation

output amplifier to be converted to an analog voltage. Continuous clocking of the device reproduces a line-by-line representation of the 190 input elements at the output.

The CCD361 can be used for a wide variety of applications. The simplest application is for delay of analog information which is accurately controlled by an external clock. Varying the clock simply changes the delay. One specific delay application appropriate to its large capacity is that of a large number of analog samples for video frame storage. This permits a time axis scan conversion where write and read rates can be varied to adapt to particular display requirements. A line of analog video information can be read in and stored at a low line rate and then read out at the higher line rate. For example, 490 active lines of the low resolution video are stored to match the 525 line input system rate (see Figure 4-19). A logic circuit is required in the video mixer (output of CCDs, see Figure 4-19) to feed 817 active lines to the 875 TV display from the stored 490 active TV lines. This logic circuit will be required to repeat 327 lines of the 490 stored lines. Therefore, one line will be repeated on the average of every 1.5 stored active line. This will result in a slight distortion. Also the LLLTV sensor will have a better resolution than the FLIR sensor.

"Write in" clock rates are generated from the FLIR sensor input sync pulses and the clock rates for CCD "read out" is generated by the 875 TV line FLIR sensor sync pulses. The "A" CCD field memory is read out in near real time, while the "B" CCD field memory is in the "write in" mode (see Figure 4-19). "Read out" and "write in" modes are alternated from field to field between "A" and "B" CCD memory units.

A block diagram of the system which stores a single field is depicted in Figure 4-20. The input demultiplexer (DEMUX-1) receives the serial video data. The first 124 lines of video are fed to DEMUX-2, while the next 124 lines are fed to DEMUX-3 (a total of 245 active lines are needed for one field).

1.0

4.5
5.0
5.6

2.8   2.5

3.2   2.2

3.6

4.0   2.0

1.1

1.8

1.25   1.4   1.6

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Each of the 124 lines is divided into thirds by the demultiplexer, the first 190 points in the line are routed to the first analog shift register, the second 190 to the second register and the third 190 to the third register (a minimum of 460 horizontal resolution elements are needed to match the vertical resolution of 350; i. e. 0. 7 Kell factor x 490 active lines x 4:3 aspect ratio). After the first 124 lines are stored in registers 1, 2, and 3, the next 124 lines are stored in registers 4, 5, and 6.

However, full-frame (two fields) storage is necessary. This requires that two field systems be combined and an additional demultiplexer and multiplexer be added.

A block diagram of the full-frame storage system is shown in Figure 4-21. The Field 1 and Field 2 systems referenced here are identical, and each is equivalent to Figure 4-20. The input demultiplexer routes the odd fields to the Field 1 system and the even fields to the Field 2 system.

Another approach to combining non-compatible raster imagery is possible when a smaller image is permissible for one sensor than for the other. If the 490 active lines of a 525-line raster are stored in a solid-state scan converter, we can clock them out directly on the 490 lines located in the center of the 875-line display. To do this a vertical blanking signal added to the storage output would simply be extended to cause the picture to begin well below the top of the 875-line display, is shown in Figure 4-22. By shortening the picture vertically, we have distorted it. The true proportions of the image can be restored by also narrowing the image by increasing the clock rate and inserting extended horizontal blanking signals. The picture now appears only in the center of the 875-line raster (Figure 4-22). The image is correct in proportion and contains all the original picture information.

The composite video signal for the image in Figure 4-22 is compatible in every way with other 875-line video, and can be mixed with the output of an
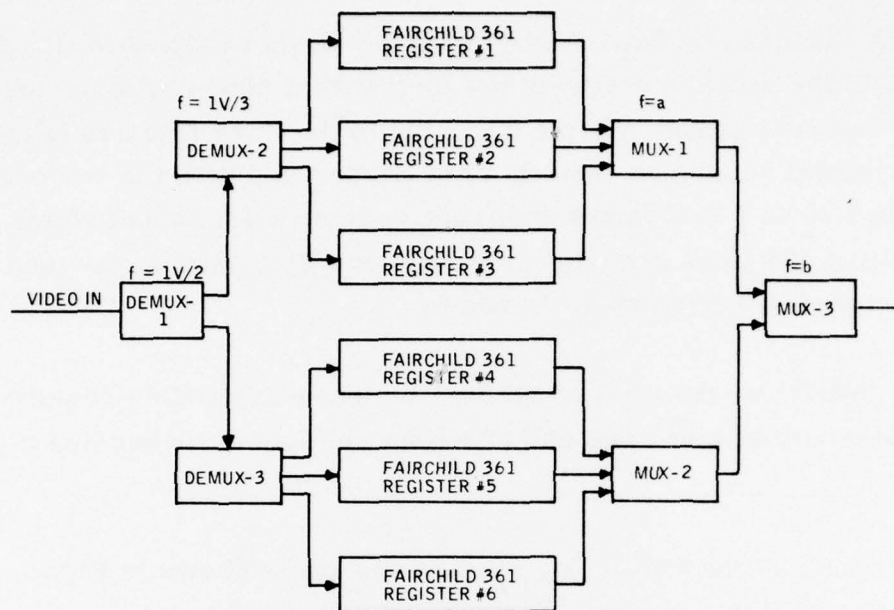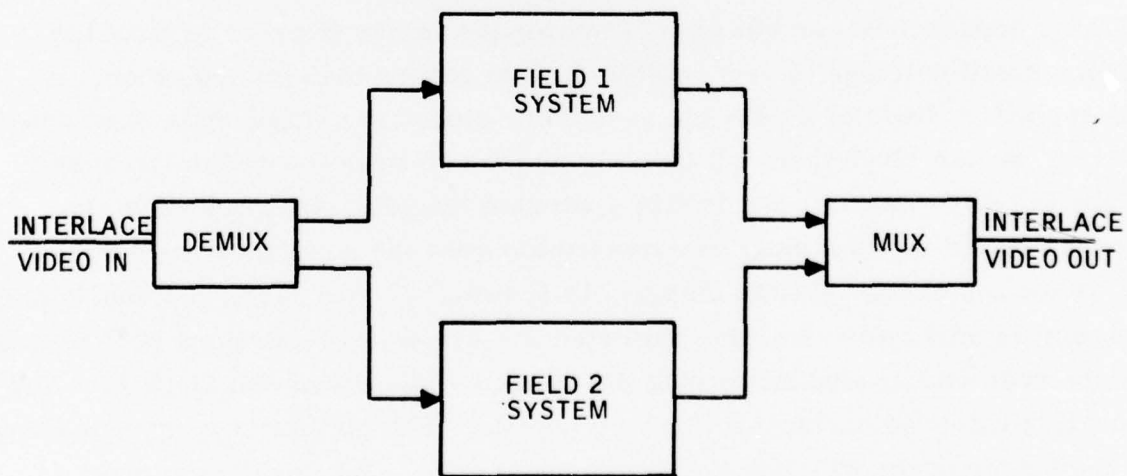
Figure 4-20. CCD Analog Field Store

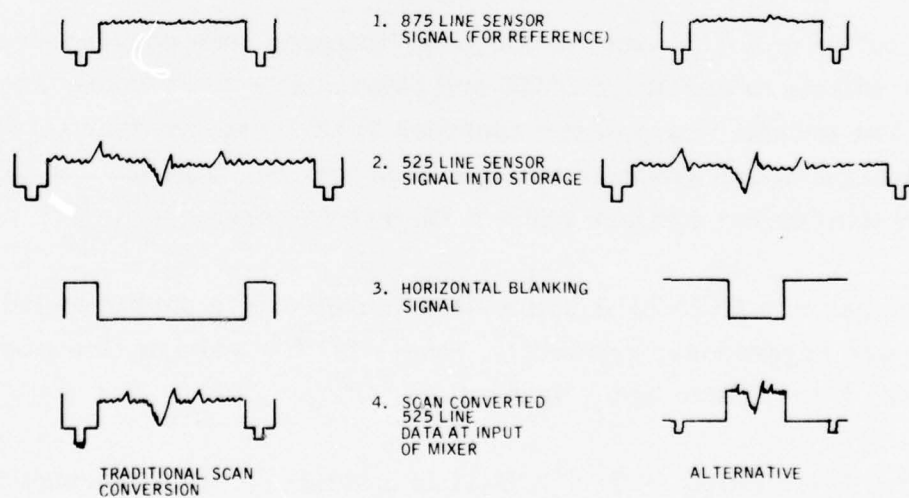Figure 4-21. Full-Frame Storage System, 30 Frames per Second

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a. 525 LINE IMAGE ON CENTER LINES OF 875 LINE DISPLAY - IMAGE DISTORTED HORIZONTALLY

b. 525 LINE DATA IMPRESSED ON CENTER PORTION OF 875 LINE ROSTER - IMAGE IN CORRECT PROPORTION

c. SCAN CONVERSION AND MIXING SYSTEM

1. 875 LINE SENSOR SIGNAL (FOR REFERENCE)

2. 525 LINE SENSOR SIGNAL INTO STORAGE

3. HORIZONTAL BLANKING SIGNAL

4. SCAN CONVERTED 525 LINE DATA AT INPUT OF MIXER
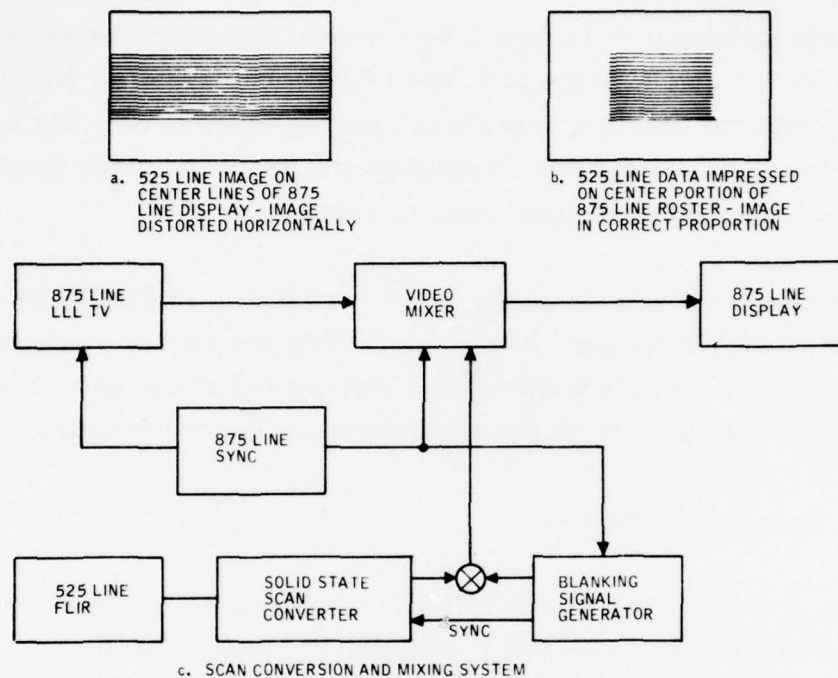
TRADITIONAL SCAN CONVERSION

ALTERNATIVE

Figure 4-22. Simplified Solid-State Scan Conversion

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875-line sensor as shown in Figure 4-22. A dual CCD solid state converter is used to store the output of the 525-line FLIR. The readout, however, is synchronized with the blanking signals generating video only in the center of the 875-line format. Figure 4-22 compares the resulting video waveforms with those from a more traditional scan converter.

The FLIR imagery will appear on the display as shown in Figure 4-22. When mixed with the LLLTV imagery it will cover only the central portion of the TV image, leaving the edges unaffected. The scaling of the two images determines the fields of view of the optics used on the two sensors.

CCD Optical Scan Conversion --

CCD Sensor -- The Fairchild CCD-221A solid-state imaging detector is a fully TV-compatible 380-element x 488-element sensor device. A camera using the CCD-221A sensor can be developed to generate TV-compatible video from slow-scan radar imagery presented on a DVST, as shown in Figure 4-23.

This application of a CCD camera for radar imagery scan conversion assumes space is available to mount the DVST and camera at a site remote from the display. The overall length of one approach to CCD camera scan conversion is 17.75 inches, which assumes an eight-inch long H-1126AP20 Tonotron, a six-inch optical object distance and a 3.75-inch camera.

The advantages of a CCD-221A solid-state sensor over a double-ended scan converter are ruggedness, reliability, longevity, low voltage, low power requirements, a small size and a light weight.

General Description -- The CCD221 is a solid-state, self-scanned area image sensor suitable for use as the sensor in camera-type applications. The device is organized in an array of 488 horizontal lines by 380 vertical columns.
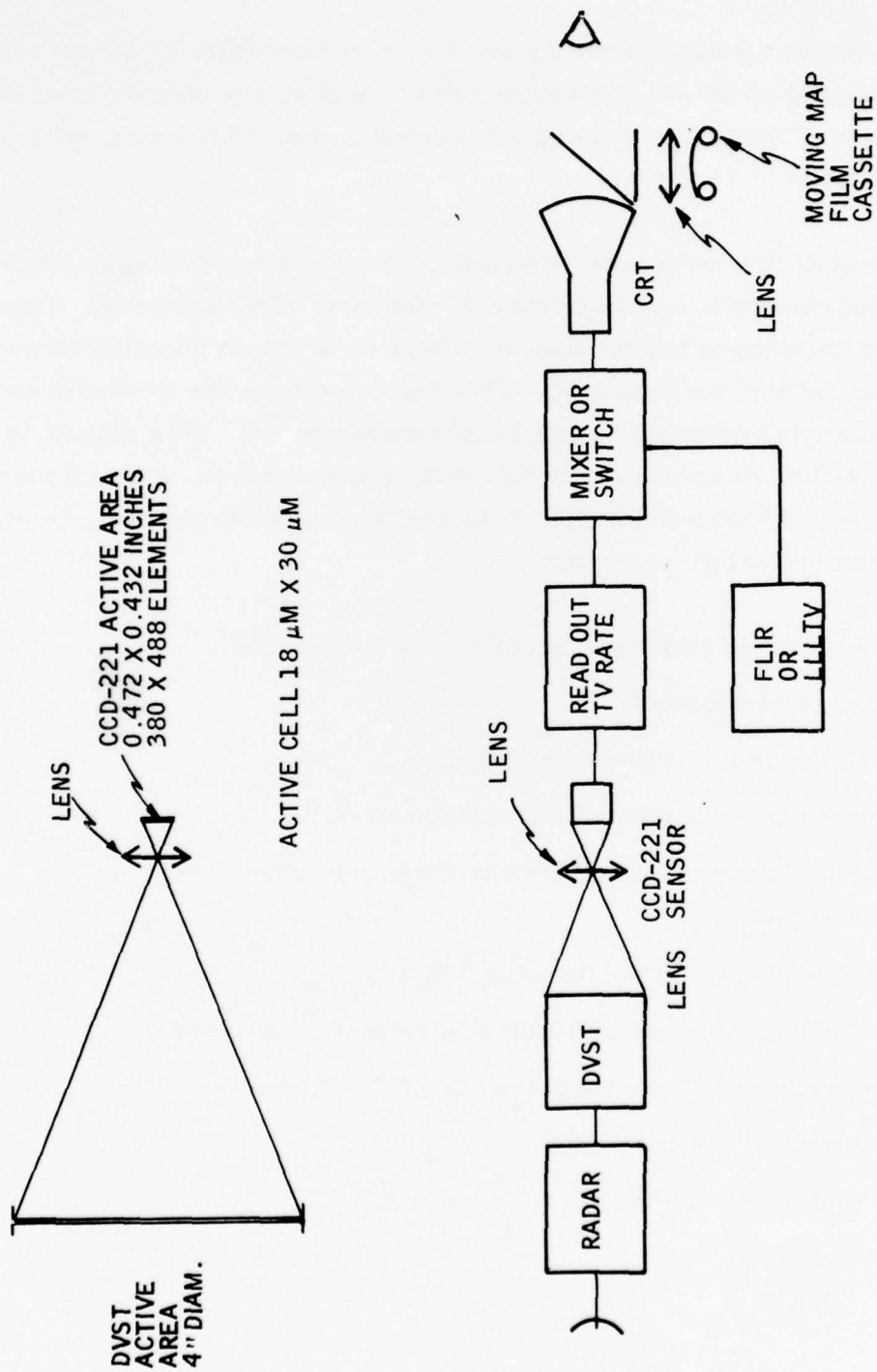
90

Figure 4-23. Radar Scan Conversion

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The 185,440-image sensing elements are 14 μm horizontally by 18 μm vertically, and are located on 30 μm horizontal centers and 18 μm vertical centers. The dimensions of the image sensing area are 8.8 mm x 11.4 mm, with a diagonal dimension of 14.4 mm.

The X-Y format of the array was selected to provide a 4 x 3 image aspect ratio and to approximate the image size of standard NTSC systems. The highly precise location of the photosites allows an accurate identification of each component of the image signal. This feature allows the device to be used in applications requiring dimensional measurement. This sensor is intended to be used in video cameras that require a low power, a small size, high sensitivity and high reliability. It is enclosed in a 36-pin dual, in-line package with an optical glass window:

- 185,440 image sensing elements on a single chip
- Column anti-blooming
- No lag, no geometric distortion
- Gamma characteristic of approximately 1.0
- On-chip video preamplifier providing more than 200mV of output signal
- High dynamic range: Typically 300:1
- Low light level capability; low noise equivalent exposure
- Wide range of video data rates, up to 75 frames/sec
- All operating voltage under 20V
- Low power dissipation: Typically 75mW
- High reliability

<u>Absolute Maximum Ratings</u> --

Operating Temperature: -25°C to 55°C
Storage Temperature: -25°C to 100°C.

<u>Voltages</u> --

10V to +15V

<u>Functional Description</u> -- Light energy incident on the image sensor elements generates a packet of electrons at each sensing element. Electrical clocking of the photogate, the vertical analog transport registers, and the horizontal analog output register sequentially delivers the charge packets to the preamplifier.

<u>Image Sensing Elements</u> -- Image photons pass through a transparent polycrystalline silicon gate structure and create hole-electron pairs in a single crystal silicon layer. The resulting photoelectrons are collected in photosites during the HIGH state of the photogate. The amount of charge accumulated is a linear function of the incident illumination intensity and of the integration period.

<u>Vertical Analog Transport Registers</u> -- Charge packets are transferred out of the array in two sequential fields of 244 lines each at the end of an integration period. Alternate lines of charge packets are transferred to their corresponding sites in the vertical registers when the photogate voltage is lowered. Clocking of the vertical register (two-phase) delivers the charge packets from the 380 vertical registers to the horizontal analog transport register. A minimum of 246 vertical transfers (246 clock cycles) are required to transport each field of charge packet out of the vertical registers. A second field cycle is initiated to receive the information from photosites corresponding to the other field (i. e., the even-numbered photoelements). Clocking of the vertical register then transports the charge packets to the output.

Horizontal Analog Transport Register -- The two-phase horizontal register has 392 elements and receives the charge packets from the vertical transport registers, line by line. Each row of information, received from the vertical registers, is serially moved to the output amplifier by two horizontal clocks.

A minimum of 392 horizontal clock pulses are required to completely transfer one row of information to the floating gate amplifier.

Floating Gate Amplifier -- Charge packets from the horizontal register are sensed by a floating gate amplifier. Its output potential is linear to the input signal charge and drives a MOS transistor. The transistor output then drives the gate of an output n-channel MOS transistor to produce a video output signal.

Optical Combining Techniques -- Optics can also be used to combine information from different sensors. This approach avoids the electronic problems of mixing incompatible E-O sensor videos and allows a choice of display tubes to match specific sensor designs (Figure 4-24). The method has several other advantages. The images do not necessarily appear at exactly the same distance from the observer; this can make the job of discrimination easier. Maintenance of the individual components can be simplified. Finally, failure of one tube or electrical part will not result in the loss of the entire display.

Figure 4-25 shows a flat combiner. The coating material can be selected to allow the proper ratio between reflected light and transmitted light (Beam 2). This is a design tool which can be used to balance the intensity of the display. The coating material can also be designed, within limits, to selectively reflect certain wavelengths of light. Combining this with a proper tube phosphor can also enhance the light balance. It is standard practice to use anti-reflective coatings on other surfaces of combiners to eliminate ghost images.
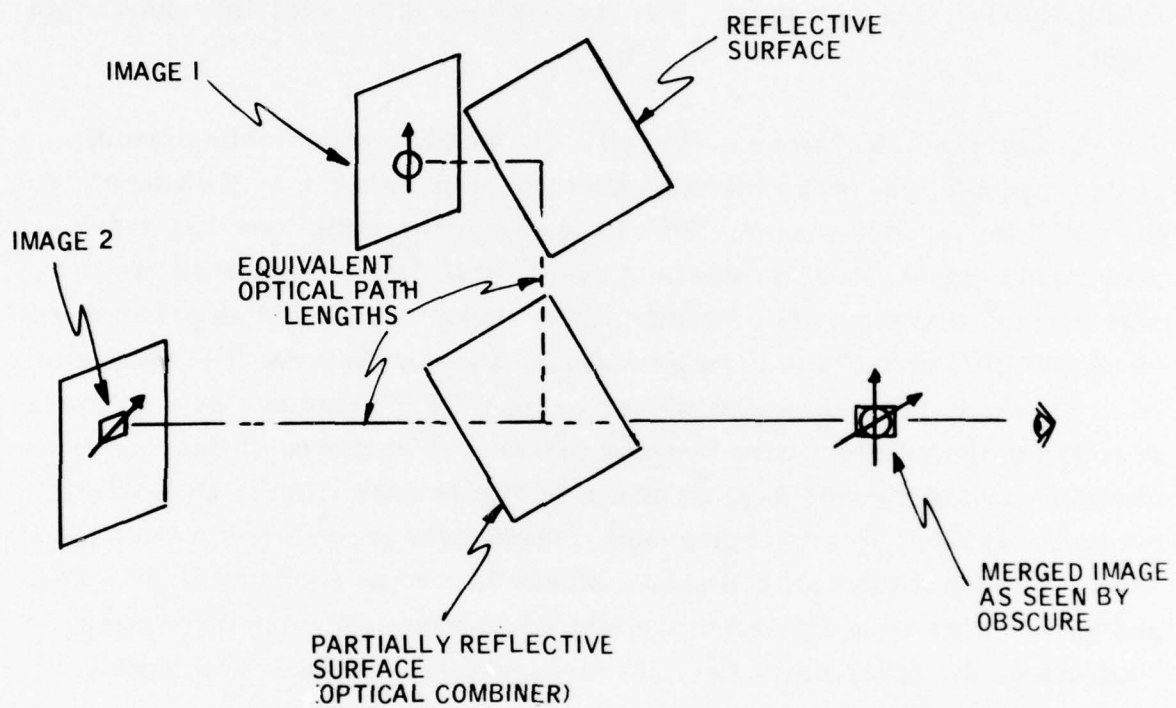
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Figure 4-24. Optical Combining Techniques

A combiner cube is shown in Figure 4-26. This combiner is used in the same way as the flat combiner, but has a significant advantage. The refractive index of the glass shortens the optical path physical distance by approximately one-third of the distance the light travels within the glass. A folding prism also has this advantage. The disadvantage of the combiner cube is its weight.

The display shown in Figure 4-27 uses a flat combiner and folding prism. In this example, the high resolution CRT could be used for an E-O sensor and the DVST for a radar sensor. Both have approximately 4-inch diameter viewing screens*. It is the smallest system that can be built using two display tubes of this size. If a folding mirror rather than a folding prism were used, the CRT would have to be moved back about an inch for it to appear to be at the same distance for the viewer as the DVST. This is a good example of reducing the system's size by using prisms. A variation of this design includes a moving map display, as shown in Figure 4-28. Here, the folding prism is replaced by a combiner cube, but the cube is modified in several ways. The top surface is elongated, part of it used as a ground glass screen and part of it as an aperture for the map projection. The map projection lens, above the cube, sends the light through the glass, onto a reflecting mirror and back onto the ground glass screen. Placing the map image at this surface of the cube provides the same viewing distance to the observer. The lens, film cassette and projection lens are similar to those previously described.

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* Thomas Electronics 5M107 CRT - 3.25 in. screen height, 4.31-in. screen width, 650-line resolution.

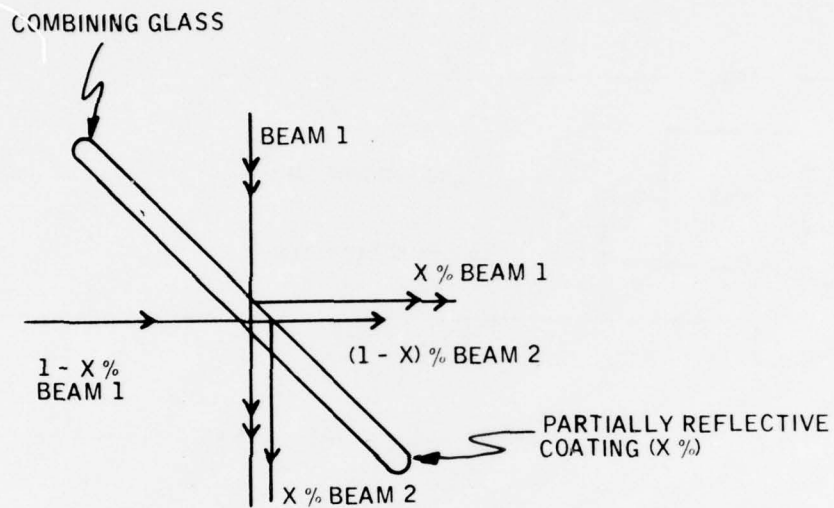Hughes Aircraft Co. Type H-1126AP20 Tonotron - 4-in. minimum screen diameter.
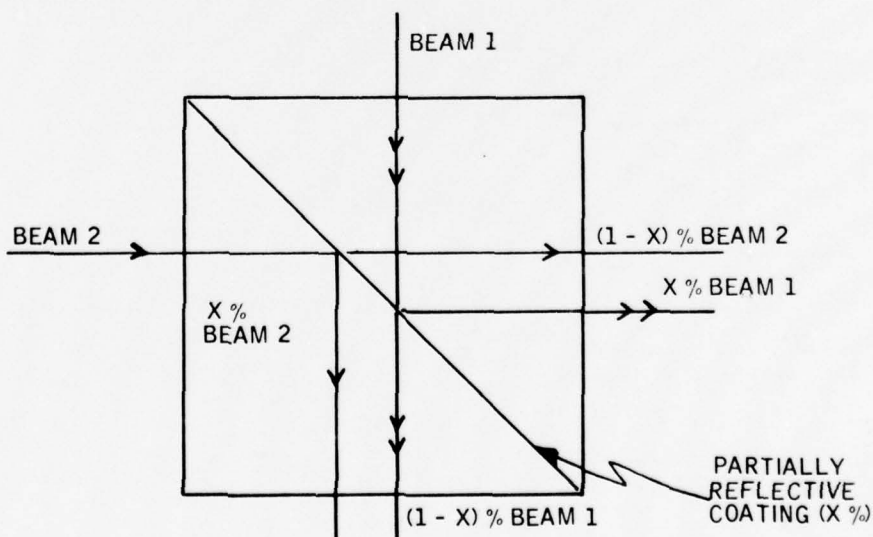
Figure 4-25. Flat-Plate Combiner
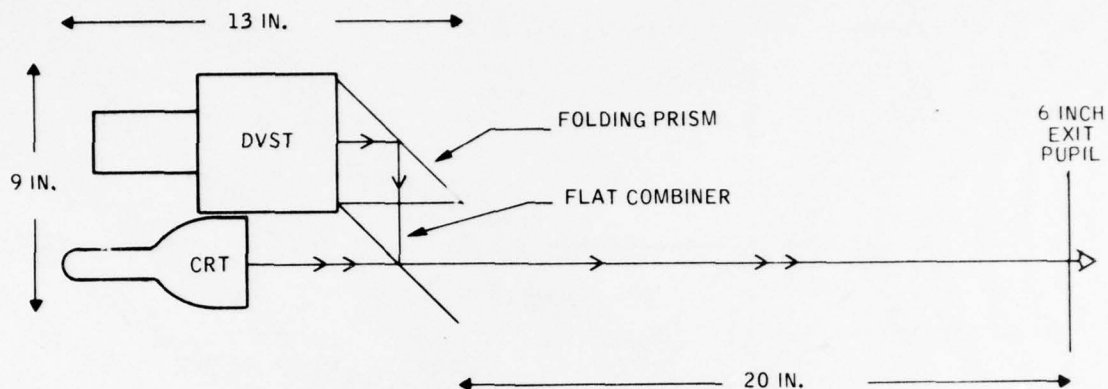

Figure 4-26. Optical Combiners

Figure 4-27. Simple Combiner Design: 27-inch Viewing Distance
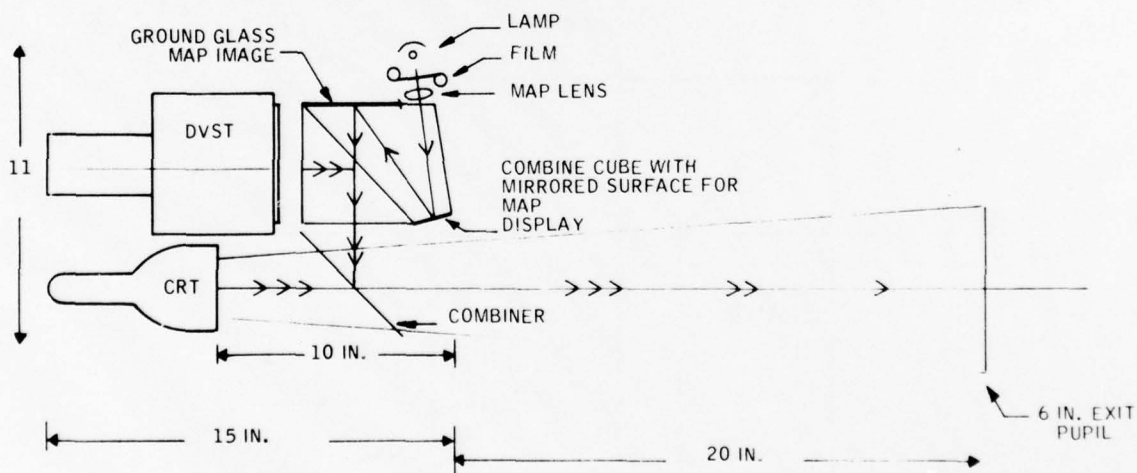

Figure 4-28. Simple Combiner Design with Map: 4-inch
Diameter Image; 27-inch Viewing Distance

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Lenses -- Lenses can be used to increase the size of the image and to transfer the image forward, near the external opening of the display. A field lens can be used to assure that light from the display enters the exit pupil. Specific lens systems for each of these tasks can only be designed for specific applications. The following does not attempt to discuss the best lens system design for some display, but rather to provide a "feel" for what can be done with lenses and for what their use implies in terms of display size, limitations of eye movement and other operational questions.

Transfer Lenses -- In the simple combiner design (Figure 4-27), the image seen by the pilot would more desirably be at the front surface of the display. This can be done using a transfer lense which can also magnify the image. For instance, if the image size desired were 6 inches, the ray trace shown in Figure 4-29 would result. The CRT and DVST face plates are 10 inches from the exit aperture of the display. To magnify the four-inch CRT image to six inches and to transfer the image to the exit aperture requires a lens with a focal length equal to 2.4 inches. However, to see the edge of the field of view at the exit pupil 20 inches away, the lens diameter required is eight inches. (This is shown by the ray label "A-B" in the figure.) The ratio of the focal length to the lens diameter is the F-number of the lens. It is practically impossible to fabricate a lens faster (lower number) than F/0.5, yet the lens shown would have to be F/0.3. This is clearly impossible and requires something be done. The usual solution is to use a field lens.

Field Lens -- Figure 4-30 shows the addition of a field lens to this design. Its optical characteristics are chosen to re-image the transfer lens at the exit pupil. In this way, the light which passes through the transfer lens is assured of entering the exit pupil, but the magnification of the system is unchanged. In this case, the field lens eases considerably the optical design of the transfer lens. It allows the lens diameter to reduce to about two inches,

yielding F/1.2. However, the field lens focal length is only 4.62 inches and, since the image size is six inches, the field lens itself is F/0.77. This is possible but still very difficult. Such a system could be constructed as shown in Figure 4-31, and would need a volume of 6 x 12 x 18 inches. The cube combiner has been shown modified to provide for a front-illuminated screen projection moving map display.
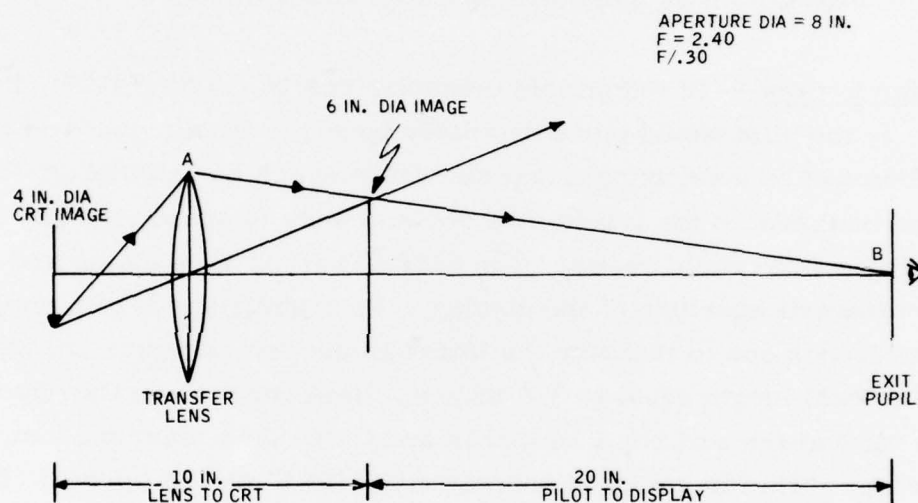

Figure 4-29. First Field Lens Design
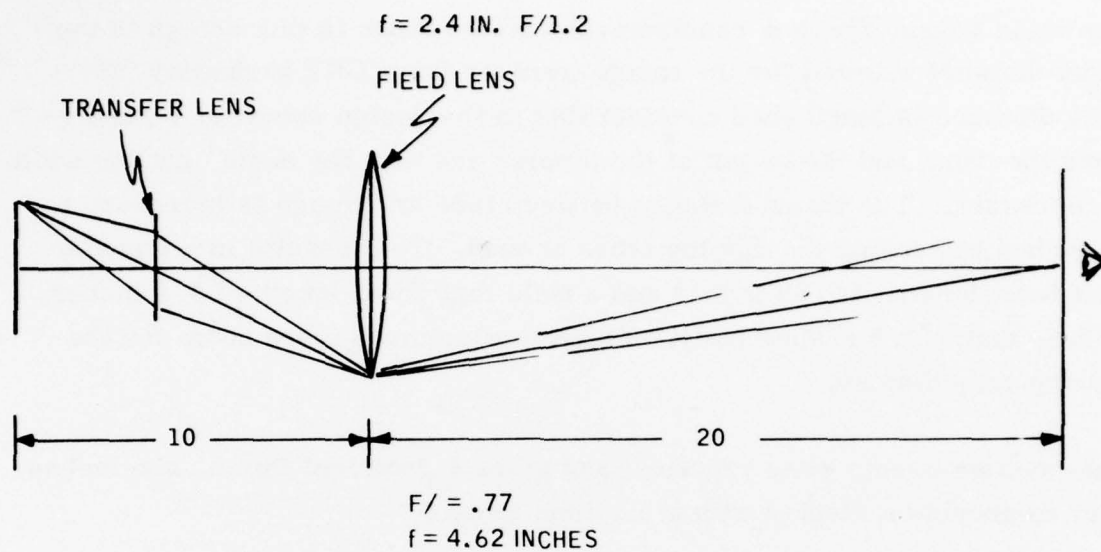
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f = 2.4 IN. F/1.2

FIELD LENS

TRANSFER LENS

F/ = .77
f = 4.62 INCHES

Figure 4-30. Field Lens

COMBINE CUBE WITH
MIRRORED SURFACE FOR
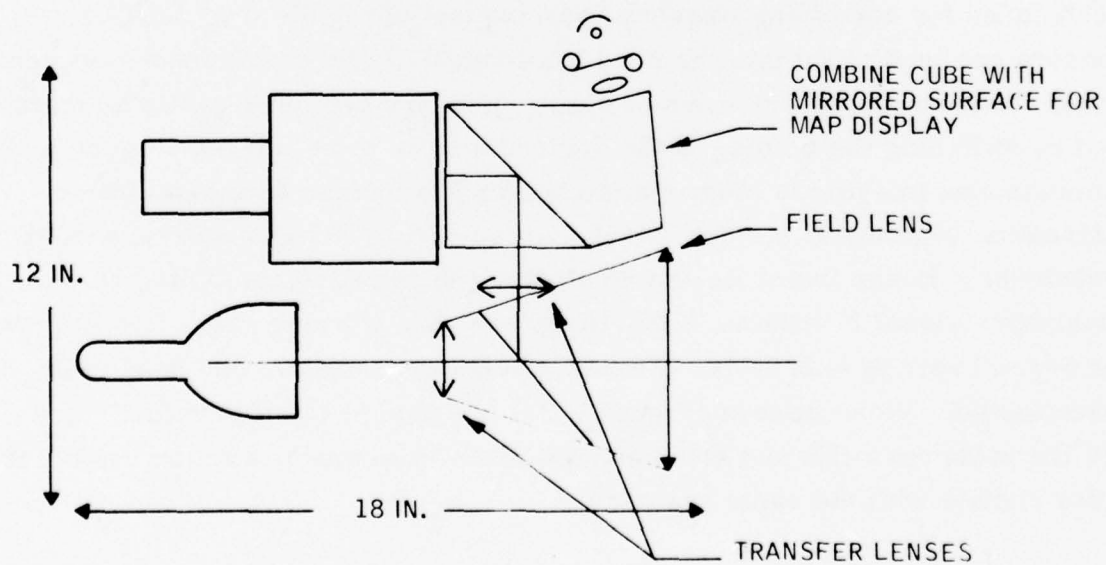MAP DISPLAY

FIELD LENS

12 IN.

18 IN.

TRANSFER LENSES

Figure 4-31. First Field Lens Design

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The main reason the lens requirements are so tough in this design is the short distance allowed for the image transfer from CRT to display face. This distance is lengthened considerably in the design shown in Figure 4-32. Here the depth and the height of the display are kept the same, but the width is increased. The throw distance between tube and image is increased to 32 inches by turning the display tubes around. This results in a transfer lens focal length of 7.68 inches and a field lens focal length of 9.8 inches, F/3.8, and F/1.6 respectively. There is also much more room for the moving-map display.

This system seems quite practical and gives a good feel for the size necessary to provide a display with a six-inch image.

Compatible FLIR and LLLTV

Techniques for combining imagery from compatible FLIR and LLLTV sensors can be divided into the need for sequential and simultaneous presentations. Sequential presentations of sensor imagery can most easily be satisfied by switching the display to the desired sensor to be imaged (Figure 4-33). Simultaneous imaging is more complicated and requires frame-to-frame alternation of images, a video mixer, a dual-beam CRT, or optical mixing techniques. Image frame-to-frame alternation requires combining by the observer's visual response. Each image now has a frame rate of 15 Hz, but the overall rate is still 60Hz. Flicker efforts are unknown and need to be investigated. Video mixers (Figure 4-33) are commercially available and are the most versatile and sophisticated of all techniques, but are limited to video signals with the same line rate.
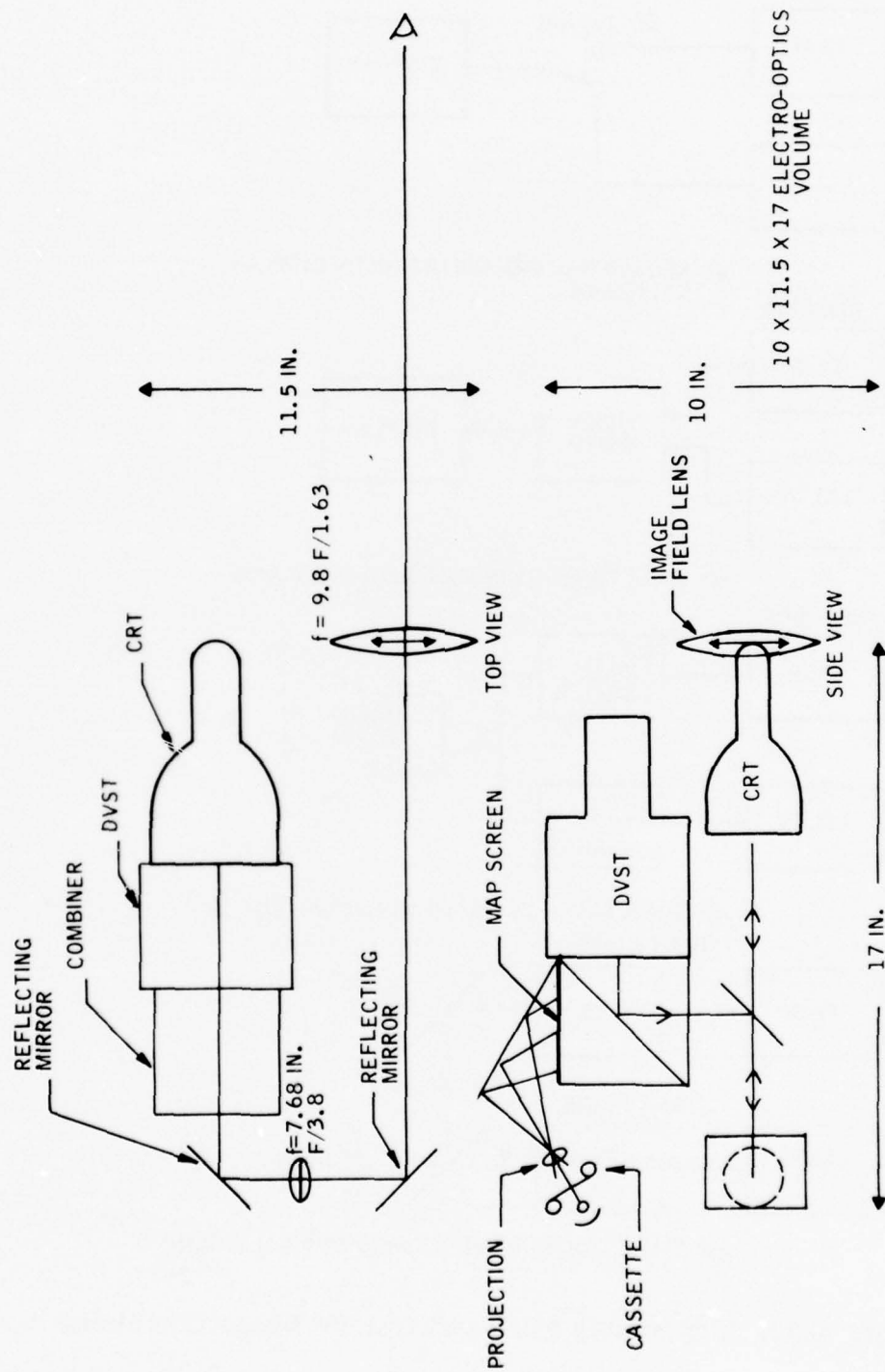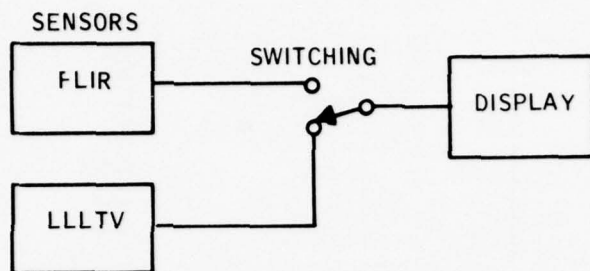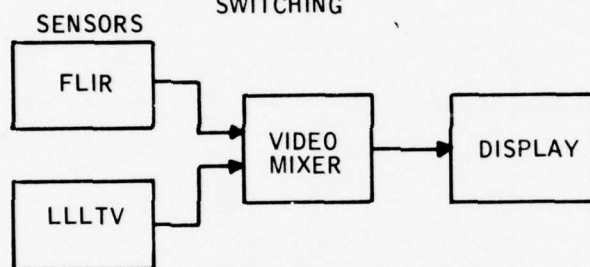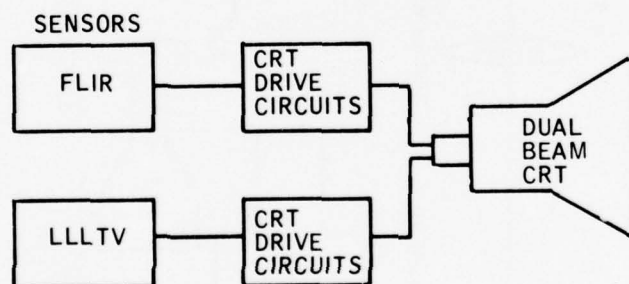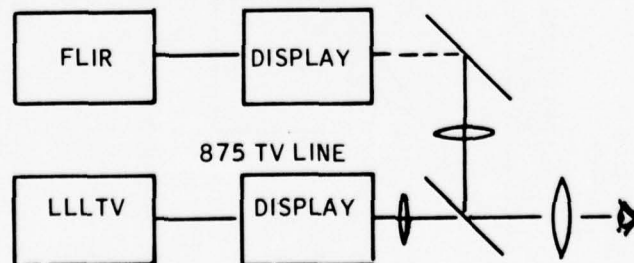
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Figure 4-32. Improved Field Lens Design

a) SEQUENTIAL PRESENTATION BY DISPLAY SWITCHING

b) SIMULTANEOUS INSERT WITH VIDEO MIXER

c) SIMULTANEOUS INSERT WITH DUAL BEAM CRT

d) SIMULTANEOUS INSERT WITH OPTICAL MIXING

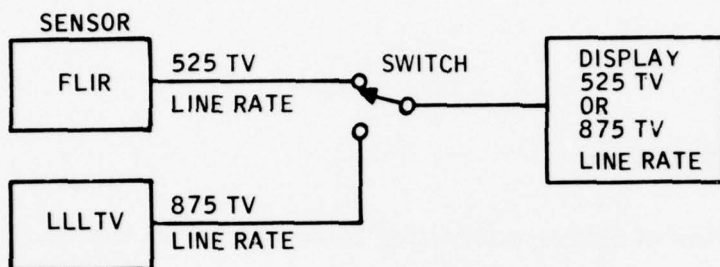Figure 4-33. Compatible FLIR and LLLTV Image Combining

Optical mixing (Figure 4-33) is certainly a possibility for image combining. However, this technique would require two CRTs as well as the separate drive circuitry. There does not appear to be a distinct advantage to this approach over the video mixer or over the dual-beam technique.
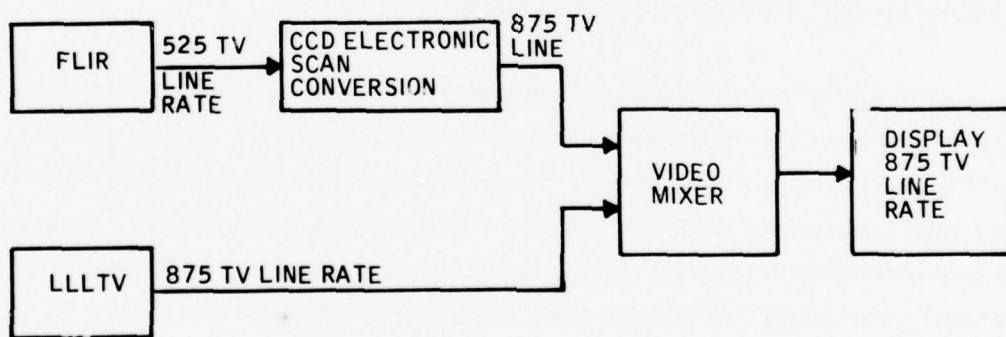
Non-Compatible FLIR and LLLTV

It is assumed for this class of image combining techniques that the FLIR sensors have a TV raster video, but that the line scan rates are not the same. For example, high-resolution, 875-line LLLTV sensors are fairly common. However, FLIR sensors of such a resolution are beyond the general state of the art. Therefore, the presentation of high-resolution LLLTV and low-resolution FLIR imagery on a single, high-resolution display may be a fairly common occurrence. Again, the techniques may be separated into the need for sequential and simultaneous presentations.

Sequential presentations of sensor imagery can best be accomplished by employing a display that operates at either sensor scan rate (Figure 4-34). These TV monitors are available. Three options are possible for the simultaneous presentation of non-compatible FLIR and LLLTV sensor images. These are alternate frame switching on the same display, CCD memory, and optical combining techniques (two separate displays, see previous section). Simultaneous presentations by alternate frame switching on one display requires the monitor to operate alternately at 15 Hz for 525 to 875 line rates.

Figure 4-34 shows the application of two Fairchild CCD-361 analog shift registers to provide electronic scan conversion of the 525-line FLIR sensor to an 875-line rate (see earlier section for a detailed discussion). This technique would require 12 Fairchild CCDs, seven demultiplexes and seven

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a) SEQUENTIAL PRESENTATION BY DISPLAY
   SWITCHING AT DIFFERENT RATES

b) SIMULTANEOUS INSERT WITH CCD
   ELECTRONIC SCAN CONVERSION

Figure 4-34.   Non-Compatible FLIR and LLLTV Image
Combining Techniques

multiplexers. In addition, logic would be required to address the multiplexer and the demultiplexers. The advantages of this form of scan conversion over scan converter tubes are volume, cost and simplicity. The output of the CCD electronic scan conversion would feed into a video mixer, as discussed in the previous section, for various forms of in-setting, fading and so forth.

Raster and Radar Image Combining

One scan conversion device and two techniques for combining non-compatible TV raster and radar images will be discussed in this section: CCD cameras; optical image combining; and dual-persistence CRT.

The CCD-221 solid-state, self-scanning sensor has the potential for scan conversion of radar imagery presented on a DVST (Figure 4-35). The resolution capability of the CCD camera is approximately equal to that of the radar sensor and DVST, and there will be some loss of image quality. A high-resolution vidicon camera would provide a better image quality, but this device is larger and less reliable. The advantages of the CCD camera are that it is small, and low in power and voltage requirements.

The CCD camera is a 525-line compatible, and its output then can be fed directly to a video mixer with a 525-line E-O sensor. However, if the E-O sensor operates at an 875-line rate, then both the video mixer and camera must operate at that rate. Video mixers at 875-lines are available and a scan converter is required to obtain 875-line rate video from the CCD camera. The CCD camera has a high sensitivity, which permits use of a slow lens as well as a reduced brightness on the DVST. This, in turn, permits a smaller spot size and improves resolution. These improvements partially overcome the image quality loss of a CCD camera. The approach requires space for remotely mounting the DVST and CCD camera.
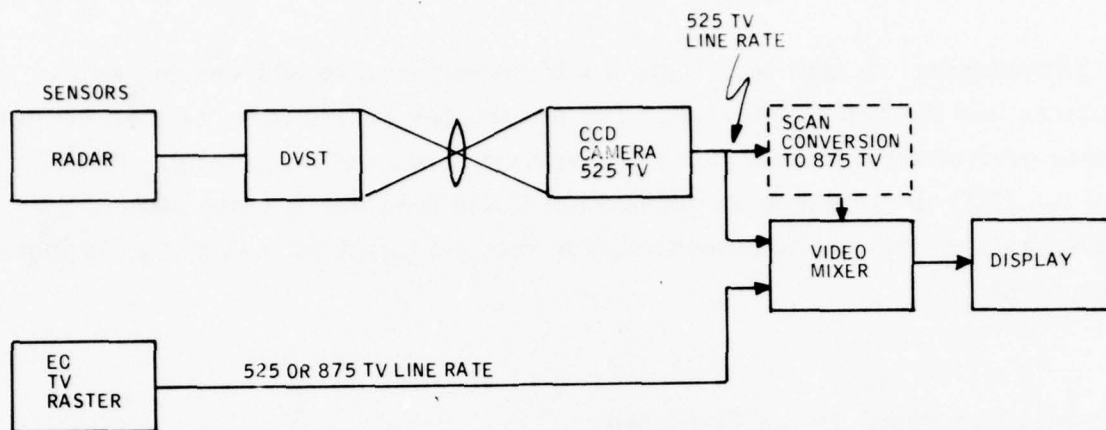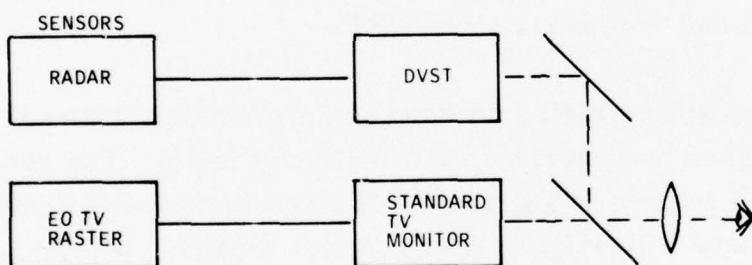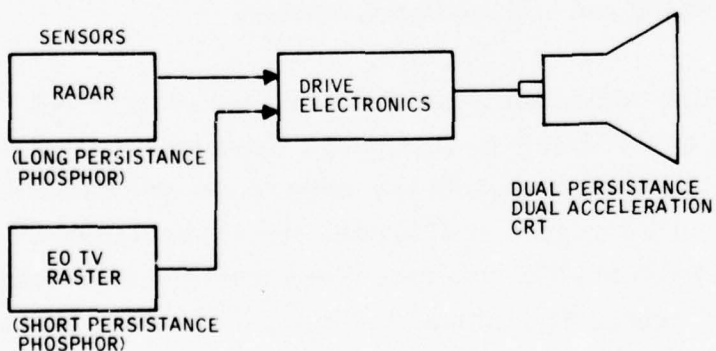
Figure 4-35. Non-Compatible TV Roster and Radar
Image Combining Techniques

The second approach to the simultaneous inserting of non-compatible E-O and radar sensor imagery is optically combining (see earlier section) with two displays, a DVST and a TV monitor.

A dual persistence phosphor CRT is the last approach considered for combining radar and TV imagery (see Figure 4-35 and previous dual phosphor CRT discussion).

Combining Symbology and Raster Imagery

Tradeoffs for combining symbology and raster imagery have been discussed (see previous discussions in Section IV).

Raster and Projected Imagery

Figure 4-36 shows one application of a rear port CRT for combining radar imagery with optical map imagery. The radar video is converted to a TV-raster format by a scan converter. Radar and E-O video can be combined by a video mixer if they are at the same TV line rates. An alternate approach to mixing map imagery with an optical combiner rather than a rear-port CRT is shown in Figure 4-36 (see earlier discussions of optical combining techniques).
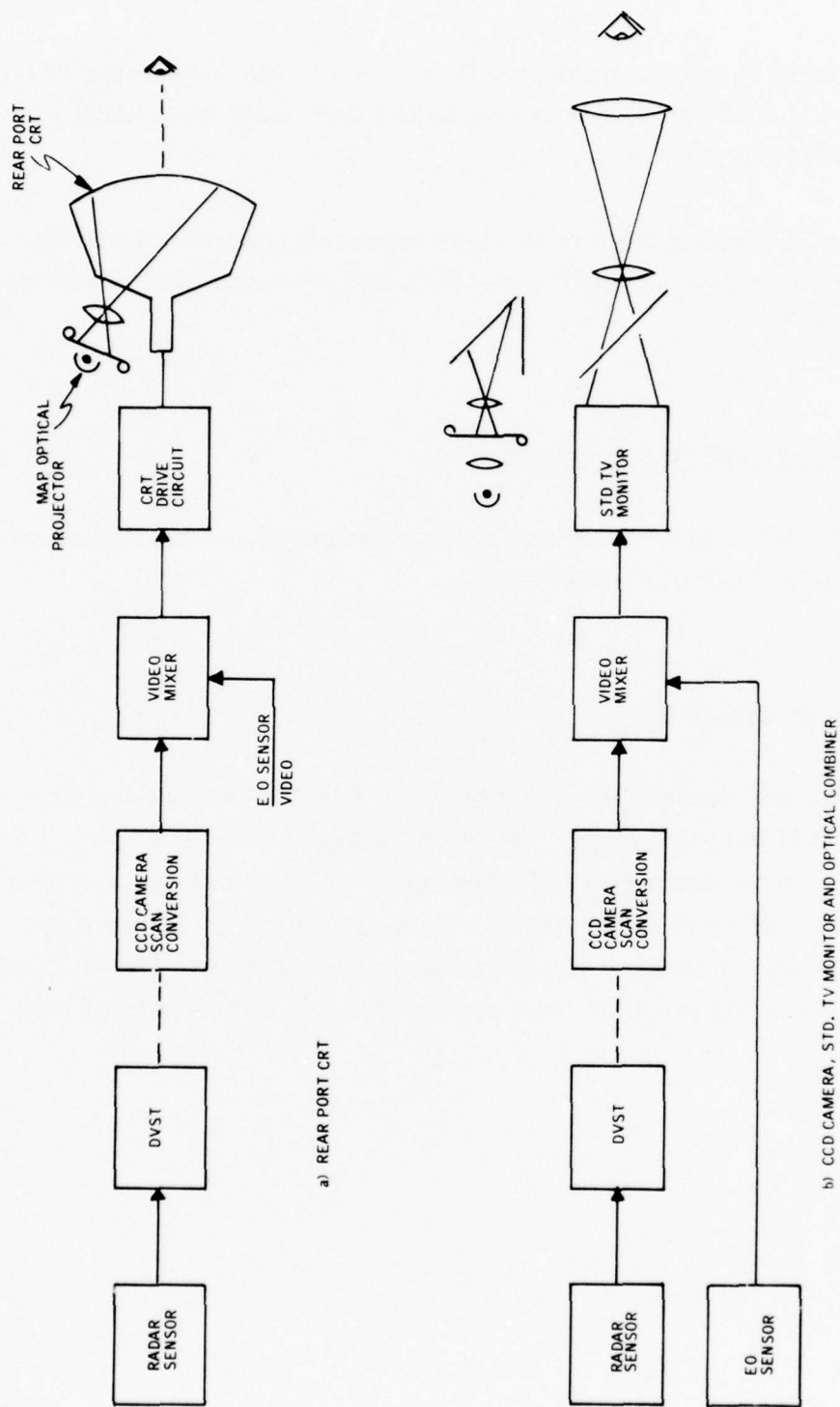
Figure 4-36. Roster and Optical Projected Imagery

a) REAR PORT CRT

b) CCD CAMERA, STD. TV MONITOR AND OPTICAL COMBINER

REAR PORT CRT

MAP OPTICAL PROJECTOR

CRT DRIVE CIRCUIT

VIDEO MIXER

E O SENSOR VIDEO

CCD CAMERA SCAN CONVERSION

DVST

RADAR SENSOR

STD TV MONITOR

VIDEO MIXER

CCD CAMERA SCAN CONVERSION

DVST

RADAR SENSOR

E O SENSOR

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SECTION V
EVALUATION

Table 5-1 provides the methodology for evaluating candidate image-combining techniques discussed in Section IV. Evaluation starts with how well hardware implementation (left, Table 5-1) satisfies the weighted display characteristics (top, Table 5-1) as shown in Table 5-1A. Display characteristics are weighed in relative order of importance, with the most important at the top.

The second step of the evaluation is concerned with the capability (Table 5-1B) of each combining approach (implementation) for generating each method of presenting multiple images (bottom, Table 5-1). The evaluation (Table 5-1C) of how well each method meets the needs of various uses for multiple imagery (right, Table 5-1) was discussed earlier in Section III and is repeated for completeness.

Table 5-1B shows one combining approach can be eliminated from further consideration at the onset and another can be reduced in importance. The dual persistence, dual acceleration potential CRT is satisfactory only for slow juxtaposition (alternation) of radar and TV imagery. Even in this application, its long-persistence phosphor has poor brightness (Table 5-1A).

A second implementation, optical combining, can only combine by super-imposition and juxtaposition when used alone (Table 5-1B). Split screen and insetting are difficult optically, however, the technique is not rejected since it is useful when used in concert with other implementation schemes.

Since all other implementations satisfy the needs of combining methods equally well, further evaluation must be based upon the weighted system character-istics (performance characteristic rating, Table 5-1A). In Table 5-2, the potential implementations are ranked in descending order of desirability, defined by this evaluation.

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Table 5-1. Evaluation and Ratings of Combining Implementations

A. Performance Characteristic Rating

Rear Port CRT	Dual Potential and Dual Persistence CRT (Radar and TV Imagery)	Tonotrons (Radar and TV Imagery)	Video Mixers (Same TV Line Rates only)	Digital Scan Conversion	Optical Combining	Image Alteration On (TV Line Rates only)	Multi-Beam CRT (Simultaneous TV Line Rates only)	Characteristic
P	P	P	G	G	G	G	G	Brightness/Visibility
G	G	G	G	G	G	G	G	Resolution
G	G	G	G	G	G	G	G	Dynamic Range/Gray Scale
P	P	G	G	G	G	G	G	Contrast/SNR/Legible
G	G	G	X	G	G	G	G	Operate at Different Line Rates
G	G	G	G	G	G	G	G	Accuracy
G	G	G	G	G	P	G	G	Low Volume
G	G	P	G	P	G	G	G	Low Cost
G	G	P	G	G	G	G	G	Reliable/Rugged/Life. Susceptibility to Magnetic Fields or Vibration
P	P	P	P	P	G	P	G	Simple
G	G	P	P	G	G	G	G	Maintenance
G	G	G	G	G	G	?	G	Flicker

Central diagram: Characteristics (A), Implementation (B), Uses (C) surrounding **Rating Tables**; Methods.

B. Implementation Rating / **C. Use Compatibility Rating**

Rear Port CRT	Dual Potential and Dual Persistence CRT (Radar and TV Imagery)	Tonotrons (Radar and TV Imagery)	Video Mixers (Same TV Line Rates only)	Digital Scan Conversion	Optical Combining	Image Alteration On (TV Line Rates only)	Multi-Beam CRT (Simultaneous TV Line Rates only)	Methods	Comparison of Two or More Distinct Images	Comparison of Two or More Superimposed Images	Monitor Two Disparate Images	Transition Between Images
G	X	G	G	G	G	G	G	Superimposition	P	M	P	P
G	G	G	G	G	G	G	G	Juxtaposition	M	P	M	M
G	X	G	G	G	NA	G	G	Split Screen	M	X	M	P
G	X	G	G	G	NA	G(D)	G	Superimposition Inset	P	M	X	X
G	X	G	G	G	NA	G(D)	G	Replacement Inset	X	M	X	M
G	X	G	G	G	NA	G(D)	G	Marker Inset	M	X	X	P
G	X	G	G	G	NA	G(D)	G	Unrelated Inset	X	X	M	P

NOTES (Tables A and B):

- G   – Good
- G(D) – Good for direct drive display
- P   – Poor
- X   – Unacceptable

NOTES (Table C):

- M – Most promising
- P – Possible
- X – Inappropriate

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Table 5-2. Image Combining Implementation Evaluation

Ranking	Implementation	Comments
1	Multibeam CRT (simultaneous TV line rates only)	Highest ranking but video inputs must be locked at same TV line rate.
2	Image Alteration (TV line rates only)	High ranking but cannot present slow scan imagery. Direct draw system. Flicker affects unknown. Inset drive circuitry is complex.
3	Digital Scan Conversion	Best overall approach with best image quality but it is complex technique with high cost at this time. AD and DA converters and digital computers are required.
4	Optical Combining	Most practical approach but must be used with other techniques. Package exceeds volume design goal (Section IV) but concept has growth potential.
5	Video Mixers (same TV line rates only)	Flexible technique for insetting but commercial equipment is limited to same TV line rates.
6	Rear Port CRT	Map imagery has low brightness and poor contrast. Inset drive circuitry complex.
7	Tonotrons (Radar and TV imagery)	Poor TV image brightness, complex five-gun arrangement, susceptible to magnetic fields and vibration. Cost is high and maintenance is a potential problem. Complex inset drive circuitry.
8	Dual Potential, Dual Persistence CRT (Radar and TV imagery)	Not acceptable.

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The multi-beam CRT and image-alternation implementations have the highest ranking (Table 5-2) of all approaches where the application is limited to TV line rate video inputs (requiring only short-persistence phosphors). Digital scan conversion is the best overall approach, but carries complexity and cost penalties. Optical combining implementation has the most promise when combined with other existing techniques, such as video mixers, map projectors and DVST. However, more design and system integration study is needed to solve packaging problems which now make optical combinations more bulky than those using electronic combining techniques.

SYMBOLOGY GENERATION

Symbol generation by either in-raster or direct-draw techniques may be required to implement multifunction image combining. When symbology is required, the type to be used must be selected by comparing the characteristics and cost of the available generation schemes with the characteristics and requirements of the display system. In general, in-raster generation will be more versatile and less costly when the display system is based on raster scanned imagery and requires alphanumerics and simple line symbols. Where more complex or higher resolution symbols are required, direct draw during the vertical fly-back period of the raster will be preferable, though it will generally be more expensive. Tradeoffs among symbol and display implementations are discussed in detail in Section IV.

SCAN CONVERSION TECHNIQUES

Digital scan conversion is truly an implementation of image combining since two video signals can be coded digitally and stored separately in memory relative to spatial location. The stored images can then be summed before readout to build up a combined image. CCD solid state and tube scan

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conversion devices, by themselves, are not complete image-combining techniques since they only convert noncompatible video to a compatible format. They are tools, however, which can be used in conjunction with combining implementation to extend the capability of a multi-image presentation.

Table 5-3 presents a ranking of how well each conversion technique satisfies the weighted display characteristics introduced in Table 5-1.

CCD electrical scan conversion has the best ranking for converting between TV line rates. Its disadvantage may be the initial fabrication and wiring of the 12 CCD memory chips. However, single, large memory chips will be available in the future. Solid-state CCD optical and single-ended tube conversion have about the same ranking. If slow-scan, low-resolution imagery at a 525 TV line output rate is needed, then the CCD approach is best. However, if slow-scan, high-resolution imagery at an 875 TV line rate (or higher) is needed, then single-ended conversion tubes are required. If careful design techniques are not followed, these devices may exact a performance penalty due to a poor signal-to-noise ratio (SNR) and poor dynamic range. Double-ended scan conversion tubes are unacceptable due to their poor accuracy, high complexity and resulting poor maintainability.

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Table 5-3. Evaluation of Scan Conversion Techniques

Scan Conversion Techniques	Rank	Brightness/Visibility	Resolution	Dynamic Range/Gray Scale	Contrast/SNR/Legible	Operate at Different Line Rates	Accuracy	Low Volume	Low Cost	Reliable/Rugged/Life Susceptibility to Magnetic Fields or Vibration	Simple	Maintenance	Flicker
CCD Electrical (TV line rates only)	1	G	G	G	G	G	G	G	G	G	P	G	G
CCD Optical	2	G	P	G	G	P	G	P	G	G	G	G	G
Single-Ended Tube	2	G	G	P	P	G	G	P	P	G	G	P	G
Double-Ended Tube	3	G	G	P	P	G	X	P	X	X	P	X	G

SECTION VI
RECOMMENDATIONS

To supplement these recommendations, the main conclusions are shown in tabular form in Section V, Table 5-1.

METHODS AND USES

Four uses of multiple images and eight methods of presenting them were identified. Of these 32 combinations, 10 appeared to be inappropriate. Eleven of the remainder seem promising, while the rest have some possibilities. All seven methods involving a single screen were promising for at least one use. However, experimental investigations are required before a definitive selection of methods can be made for each use.

We recommend the following approach to research in this area. First, the Navy should assign priorities to the four uses of multiple image presentation. Those uses of concern should be investigated, beginning with that judged to be most important.

Appropriate imagery would be selected, or developed, as necessary. The candidate presentation methods would be simulated. Experiments would be conducted. In these, the various presentation methods under investigation would be used to show the selected imagery to observers. The response of the observers to this imagery would be recorded. The response data would be analyzed and used to compare the relative merits of the presentation methods. The method associated with the most effective performance would be recommended.

This procedure should be repeated for each use that the Navy judges to be important.

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If the information composite use were selected, several types of image content relationship should be used. In one case, the two images from different sensors should have an identical pointing angle, scale and geometry. In addition, imagery should be used in which pointing angle, scale and geometry are varied in such a way as to provide partially related imagery. Completely unrelated imagery would be of no interest in this study.

If one investigated the composite image use, similar imagery content relationships should be used. In addition, the imagery sample used should include examples of overlaying, spotlighting and replacement (as discussed in Section III).

Different imagery would be required for investigating the third use. When parallel information sources are monitored, the two images being viewed are likely to have little or no relationship in terms of content. However, a number of image pairs should be used. For example, LLLTV and FLIR, LLLTV and radar, radar and map imagery, and FLIR and symbolic information. This list is illustrative, not exhaustive.

It would be appropriate to investigate methods of making transitions in the context of target acquisition or reconnaissance. The imagery used and the instructions to the observers would maximize the need for transitions. Changes between various image sources should be investigated; for example, from map to radar, from radar to LLLTV and from LLLTV to FLIR.

A general approach to research in this area is summarized below:

Task 1. Prioritize the four uses of multiple-image presentation.

Task 2. Design experiments that investigate the use of highest priority.

Task 3.   Prepare suitable imagery.

Task 4.   Construct an apparatus capable of producing the appropriate methods of multiple-image presentation.

Task 5.   Conduct experiments to measure the performance of human observers for each presentation method.

Task 6.   Analyze data, comparing performance for each presentation method.

Task 7.   Report findings, recommend best method(s) of presentation for particular use investigated.

Research should be conducted on all of the uses deemed to be important. This is the only way to produce definitive answers linking methods to uses of multiple-image presentation.

IMPLEMENTATION

We identified seven different methods of presenting multiple images on a single screen.   Eight techniques or devices were located that could be used in implementing these methods.   The characteristics of all eight were investigated and evaluated.   To carry this analysis further and to obtain more specific, applied data, it will be necessary to relate potential systems to particular aircraft, sensors and missions.

We recommend the following program to generate more specific data.

Task 1

Either choose a specific aircraft with specific missions, or develop a hypothetical model of an aircraft with specific hypothetical missions. By analysis, define a sensor complement to carry out the missions. To perform this analysis, consideration must be given to target type, background and clutter, operating environment, sensor resolution, field(s)-of-view, and number of members in the crew and their workload.

Task 2

Define a multi-sensor display system to bring together the outputs of the sensors defined above, annotate them with needed symbology, and present them in the format(s) which will make them most useful to the aircrew. This analysis requires reference to all the data listed above. In addition, the flight scenario (day or night, etc.), restrictions on operation (positive visual identification before attack, etc.); type of visual access required (head up or head down), and the need for auxiliary information (attitude or air data, etc.) will be of interest. A significant part of the task will be to choose those implementation techniques which offer the greatest opportunity for improvement over existing techniques at an acceptable cost.

Task 3

Fabricate a demonstration model of the chosen multi-function display and conduct a laboratory evaluation of its performance. Depending on resources available, the demonstration model may be designed either for laboratory-only analysis or for an eventual flight test. The latter is preferable, though the former would yield information valuable in designing a flight system.

CONCLUDING REMARKS

We have made a number of tentative recommendations. We feel that much more work is required in both research and development. The design of cockpit information systems has been of great importance, and the development of multifunctional and multisensor displays makes this task even more challenging.

APPENDIX A
LUMINANCE AND CONTRAST REQUIREMENTS

Luminance of emissive displays is reduced if the active elements are not on during the 0.1 second integration time of the eye. Most display materials are quoted for their peak luminance unless it is the time-averaged luminance of the display that is measured. It is necessary to know the refresh rate of a display when it is multiplexed or matrix addressed to establish the relationship between the required peak luminance (B_R) and desired time-averaged luminance (B).

$$B_R = \frac{B \times L}{N} \qquad \text{(A1)}$$

where

N = number of refresh periods during 0.1 second integration time of the eye.

L = number of characters to be sequentially multiplexed or the number of lines of a matrix display being driven one line at a time.

The required peak luminance must be 170 times the time-average of brightness for a 500-line matrix address display with a 30 TV frame rate. It is apparent that a display with intrinsic or on-site memory would greatly improve display luminance as the driven element would be on during the entire refresh period.

The luminance of a display (instantaneous threshold) must be at least 1/100 of the luminance level of the surroundings (to which the eye is adapted) to be visible. However, this data was from test of a black square with an angular subtend against a white background, and a smaller ratio of 2/100 or 5/100 should probably be used for a/c displays Therefore, an aircraft display should have a luminance of from 680 to 1700 cd/m^2 to be visible with the eye adapted to the luminance levels of white clouds (i.e., 34 000 cd/m^2).

The intrinsic contrast between on and off elements of a display are degraded when that display is multiplexed. The relationship of the required display intrinsic contrast ratio (C_R) to the desired time-averaged contrast ratio (C) is

$$C_R = \frac{C \times L}{N} \qquad \text{(A2)}$$

The intrinsic contrast between cells is measured when the display element is on over the entire integration time of the eye. The time-averaged contrast is measured while the display is being multiplexed or matrix addressed and the display cell is not on continuously. If a time-averaged contrast of 10:1 is required, then an intrinsic contrast of 1700:1 is required for a 500-line matrix display with a 30 frame refresh rate (N = 3.0). Because few display materials have this high of an intrinsic contrast, on-site memory is needed for matrix addressed passive displays.

This contrast expression (Equation A2) is valid for a passive reflective display under any conditions of ambient illumination as the luminance ratio is the same as the contrast ratio. However, the contrast of an active display is degraded by any ambient illumination on the display due to direct sun illuminance or ambient illuminance from the sky. The time-averaged contrast (C) of an active display is also

$$C = C_R \frac{N}{L} \qquad \text{(A3)}$$

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or

$$C = \frac{B_{Hi}}{B_{Lo}} \; \frac{N}{L} \tag{A3a}$$

where B_{Hi} is the peak cell brightness during the on time, and B_{Lo} is the average cell brightness during the off time.

The time-averaged contrast ratio changes when the luminance due to the effective display reflectance (R) with an incident illumination (E) is added to the intrinsic cell luminance levels B_{Hi} and B_{Lo}:

$$C = \frac{(B_{Hi} + R\,E/\pi)}{(B_{Lo} + R\,E/\pi)} \; \frac{N}{L} \tag{A4}$$

or

$$C = \frac{(B_{Hi} + R\,E/\pi)}{(B_{Hi}/C_R + R\,E/\pi)} \; \frac{N}{L} \tag{A4a}$$

It can be seen that the time-averaged contrast is reduced by any illuminance on the display. The required (peak) display luminance (B_{Hi}) during the cell on time is found from the above equation to be

$$B_{Hi} = \frac{RE(N/L - C)}{\pi\,(C/CR - N/L)} \tag{A5}$$

An example of increased display luminance requirements is given here for explanation. Direct sun illuminance is about 100 000 lm/m^2. Ambient illuminance (E_C) on the display from white cloud luminance (B_C) over a solid angle (Ω) of 1.6 steradians (estimate of solid angle of white, bright clouds through cockpit windows) is approximated as

$$E_C = \frac{\Omega\,B_C}{2} \tag{A6}$$

$$E_C = \frac{1.6 \times 34\,000\,cd/m^2}{2}$$

$$E_C = 28\,000\; lm/m^2$$

A nonmultiplex display (N/L = 1.0) in direct sunlight with an intrinsic contrast ratio (C_R) of 100:1, a desired display contrast (C) of 10 with a cell reflectance of 0.05 would require an intrinsic peak luminance (B_{Hi}) of

$$B_{Hi} = \frac{RE\,(1 - C)}{\pi\,(C/C_R - 1)} \tag{A7}$$

In substituting for the case of direct sun illumination,

$$B_{Hi} = \frac{0.05 \times 10^5}{\pi} \; \frac{(1 - 10)}{(10/100 - 1)}$$

$B_{Hi} = 16,000\,cd/m^2$ and in cloud ambient illumination, $B_{Hi} = 4456\,cd/m^2$.

It should be noted that as the intrinsic contrast (C_R) approaches the required contrast (C) or when C/C_R becomes unity, the display luminance requirement becomes infinite. It can be concluded that the intrinsic contrast of a nonmultiplexed display should be roughly ten times the desired display contrast to avoid unreasonable display brightness requirements in an aircraft.

The display luminance and intrinsic contrast ratio requirements for a matrix line-at-a-time display becomes severe in the ambient illumination of an aircraft cockpit. The required peak display intrinsic luminance is

$$B_{Hi} = \frac{RE\ (N/L - C)}{\pi\ (C/C_R - N/L)} \tag{A8}$$

The numerator is negative as N/L is less than C for matrix displays. Therefore, C/C_R must be less than N/L to have a positive (real) solution for the display peak luminance. If C/C_R is to be 10 times less than N/L to minimize the peak luminance requirements, then the intrinsic contrast (C_R) must be 17 000:1. This is for the matrix display case for C = 10, L = 500 lines, and N = 3.

$$C_R > 10\ \frac{CL}{N} \tag{A9}$$

$$C_R > \frac{10 \times 10 \times 500}{3}$$

$$C_R > 16\ 660:1$$

This high contrast is expected because matrix address cell elements are on for a short time, making residual luminance of the "off" cells significant. Therefore, it is critical that there be very little drive leakage to the off cells, i.e., the off cells residual luminance must be 17 000 times less than the peak luminance of the on cell. The peak display luminance requirement for this case in direct sunlight is

$$B_{Hi} = \frac{0.05 \times 10^5\ (3/500 - 10)}{\pi\ (10/17\ 000 - 3/500)} \tag{A10}$$

$$B_{Hi} = 3.0 \times 10^6\ cd/m^2\ \text{for direct sun luminance}$$

$$B_{Hi} = 8.2 \times 10^6\ cd/m^2\ \text{for ambient sky luminance}$$

These luminance levels are very high compared to what is available for flat panel materials. The best solution for matrix displays in an aircraft is to develop on-site intrinsic or inherent memory capability; it can be concluded that development of on-site memory is a firm requirement for active matrix addressed displays in an aircraft.

This analysis does not account for the improvement of display contrast and reduction of display brightness through the use of ambient light suppression face plates, louvers, or filters because these devices will probably not reduce the brightness or contrast requirements of a nonmemory active display to a reasonable level. These devices, however, will permit some active nonmultiplex displays or a matrix display with on-site memory to function in ambient illumination. Operation in direct sun may be possible only for a passive display in the nonmultiplex mode.

REFERENCES

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